

HISTORIC CONCRETE

FROM CONCRETE REPAIR TO
CONCRETE CONSERVATION

by
Herdis A. Heinemann

Historic Concrete

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Concrete Conservation

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PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus Prof.ir. K.C.A.M. Luyben,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen
op donderdag 7 februari 2013 om 10.00 uur
door

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Geboren te Wolfratshausen, Duitsland.

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Dr. T. G. Nijland heeft als begeleider in belangrijke mate aan de totstandkoming van het proefschrift bijgedragen.

ISBN 9789052694115

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Typeset with the L^AT_EX Documentation System.

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aos meus marotos, and to my family.

Acknowledgements

Conducting a PhD is never the work of a single person, despite what is written on the cover. Many people gave me support through the years, and we shared good and bad times.

I would like to thank my supervisors, Prof. ir. Rob van Hees, Dr. Hielkje Zijlstra and Dr. Timo Nijland. Thank you for giving me the opportunity to carry out this research, and especially giving me the freedom to explore my own topic. Each of you gave an unique contribution to this work and helped me to grow as a scientist and as a person. I will definitely miss our meetings, which were, besides friendly, enriching due to our diverse professional and cultural backgrounds.

I would like to thank my committee members - Prof. dr. Marieke Kuipers, Prof. dr. Ir.-Arch. Ine Wouters, Prof. dr. rer. nat. Bernhard Middendorf, Prof. dr. Rob Polder and Prof. dr. ir. Erik Schlangen - for their time and effort, and participation in the defense.

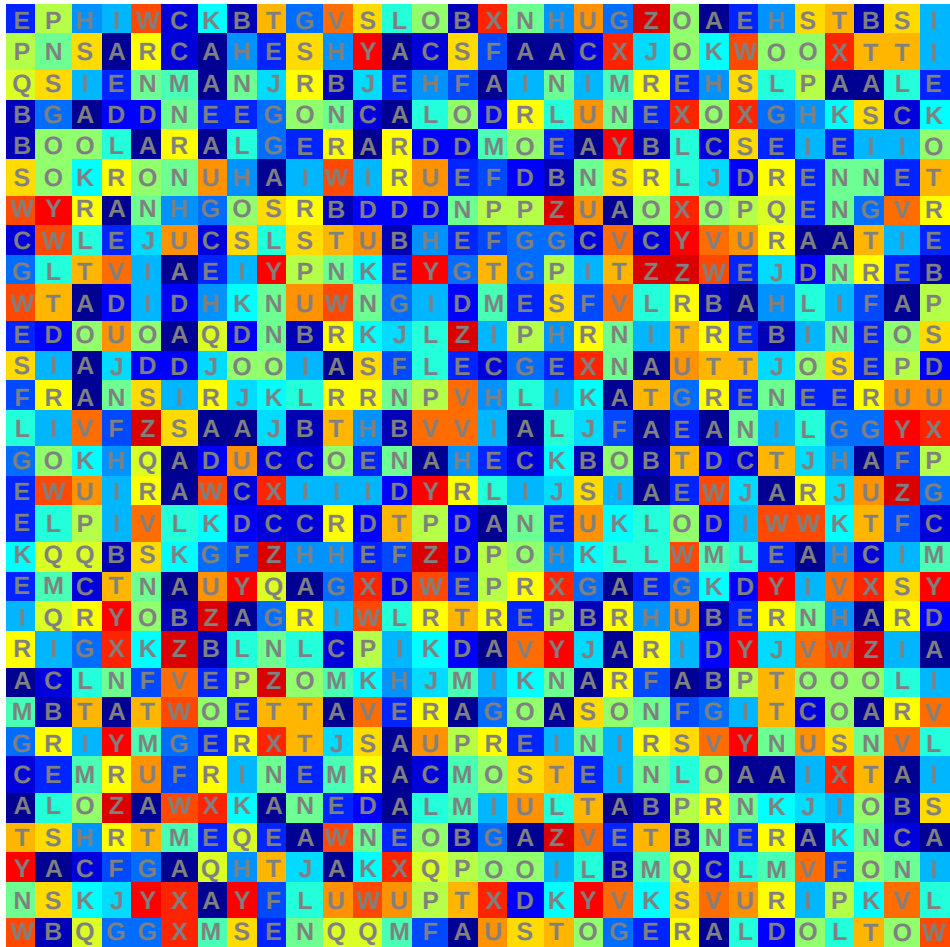
To my former colleagues at RMIT: thanks for your support and language lessons - both Dutch and Italian. I will never forget what a *hoenderei* is - mille grazie!

I would like to express my gratitude towards TNO Delft, for their generous support and giving us shelter after the burning of our faculty on May 13th 2008. My thanks also to the former rector magnificus Prof. dr. ir. J. T. Fokkema, for the moral support he gave us Phd students of the Faculty of Architecture in the period after the fire.

Besides my official PhD group, I would like to thank the group of Wind Energy of the Faculty of Aerospace for the friendship and social life during my PhD period, and the group of Materials and Environment at the Faculty of Civil Engineering for updating me on the 21st century science of materials.

My apologies to my family and friends for cutting down my social life in the last years. Thank you for holding on and supporting us. Queria agradecer ao meu marido Carlos - sem ti este livrinho nunca seria o que é, e por me dares coragem para começar e acabar o doutoramento. Muito obrigada! Und vielen Dank an Fausto, der mir gezeigt hat, dass es noch viel mehr auf der Welt gibt und warum wir Denkmäler beschützten sollten.

Danke, Herdis



Summary

Concrete like materials were already applied during the Roman Empire. After the decline of the Roman Empire, a wide scale application of concrete only reappeared in the 19th century. Here lies also the origin of modern (reinforced) concrete. Since then, both concrete application and composition have significantly changed. Today, concrete from the 19th and early 20th century is considered as historic concrete.

In this thesis, we study historic concrete in the Netherlands, that is to say the concrete dating back from the middle of the 19th century up to the 1960s. Within this period, the application and properties of concrete varied, due to increasing technological insight and social acceptance of concrete as a building material.

Although the application of concrete in the Netherlands was late compared with neighbouring countries, there are quite specific and interesting developments and innovations in Dutch concrete, especially with regard to surface finishes. Historic concrete in the Netherlands is thus specific enough to require a dedicated study. In addition to this, the commonality of the history of concrete in different countries makes the relevance of this study broader than the Dutch case.

Knowledge on historic concrete is increasingly relevant, as conservation of historic buildings dating from the 19th and 20th century internationally emerges as a new field within heritage care. This period is characterised by both architectural and structural innovations and by novel construction materials, of which (reinforced) concrete is probably the most important. Although a growing number of concrete buildings is listed as monuments, conservation specialists have still to become acquainted with the history and properties of historic concrete. Even though the structural history is frequently addressed, only little is known about the composition and surface finish of historic concrete.

For the conservation of historic concrete buildings, generally ordinary repair techniques, which have been developed for modern concrete, are applied. From a technical point of view, their performance is not always satisfactory, as the properties of historic concrete can deviate from modern concrete. From a conservation point of view, additional threats exist, because requirements such as respecting the historic material and heritage values are commonly not considered. An uncritical application of repair approaches and a lack of knowledge on historic concrete induce the risk of loss of historic evidence and historic material.

Therefore, the aim of this thesis is to develop a real concrete conservation approach, which takes into account the specific properties and the heritage values of historic concrete.

The main research questions are therefore the following:

- *How can historic concrete be preserved together with its ascribed heritage values?*
- *How can a proposed conservation strategy be evaluated for its impact on both the heritage values and the technical performance?*
- *How can we balance the technical demands and the preservation of heritage values, when heritage values and durability issues originate in the same material properties?*

The structure of the thesis reflects its aim to achieve a dedicated conservation strategy for historic concrete:

Part I - Understanding and characterisation of historic concrete

The first part offers a compendium of historic concrete addressing the development of design rules and standards in the Netherlands, and in particular the constituents used (binders, aggregates, mixing water), mix design, reinforcement, and surface finishes applied. This part is illustrated with Dutch examples, supporting both technical and historical surveys in the field, and offers historical background information for further (material) investigation.

Part II - Interpretation and evaluation of historic concrete

The second part gives guidance to identify risks for both material and heritage values. This includes methods to correlate heritage values with the historic concrete and the state of conservation. Additionally, the risks and benefits of different repair techniques are evaluated from a conservation point of view. The new approach is applied to three case studies: Fort Bezuiden Spaarndam (1897-1901), the Hofplein railway viaduct (1900-1908, A.C.C.G. van Hemert), and the earth retaining walls for the unfinished Groot Museum (1921, H. van der Velde).

Part III - Development and evaluation of dedicated conservation strategy

The concluding part addresses the decisions to be made when developing a dedicated conservation strategy. The proposed approach considers balancing the preservation of heritage values and technical demands. Case specific criteria are formulated, which allow the characterisation of possible conservation strategies.

This thesis presents new knowledge on historic concrete, combining historical developments with material properties. Different periods within the life in service of concrete are linked: the past by explaining its possible significance and durability, the present by evaluating its in practice performance and state of conservation, and the future by supporting decisions on an appropriate conservation strategy.

This thesis aims to strongly support the necessary transition from concrete repair to concrete conservation.

Delft, 2012

Herdis Heinemann

Samenvatting

Al in de Romeinse tijd werden betonachtige materialen toegepast. Na de ondergang van het Romeinse Rijk duurde het tot in de negentiende eeuw voordat beton weer op grote schaal toepassing vond. In die periode ontstond het moderne (gewapende) beton. Overigens zijn de toepassing en samenstelling van beton intussen substantieel veranderd. Beton uit de periode van herintroductie wordt als historisch beton beschouwd.

Dit proefschrift vormt het resultaat van onderzoek naar historisch beton in Nederland. Beton dat is geproduceerd vanaf het midden van de negentiende eeuw tot de jaren zestig van de twintigste eeuw beschouwen we als 'historisch beton'. Binnen deze periode varieerden de toepassing en de eigenschappen van beton door voortschrijdend technologisch inzicht en door de maatschappelijke acceptatie van beton als bouw materiaal.

De toepassing van beton in Nederland kwam later op gang dan in de buurlanden. Niettemin zijn er specifieke en interessante ontwikkelingen en innovaties in Nederlands beton, vooral met betrekking tot oppervlaktetechnieken. Dit vormt voldoende argument om Nederlands historisch beton op zichzelf te onderzoeken. Dat overigens historisch beton in verschillende landen ook duidelijke overeenkomsten vertoont, maakt de relevantie van deze studie breder dan alleen de Nederlandse situatie.

Kennis van historisch beton wordt steeds relevanter, omdat restauratie van historische gebouwen uit de negentiende en twintigste eeuw internationaal als een nieuw gebied binnen de monumentenzorg naar voren komt. Deze periode wordt gekenmerkt door zowel architectonische als constructieve innovaties en door nieuwe bouwmaterialen, waarvan (gewapend) beton wellicht het belangrijkste is. Hoewel een groeiend aantal gebouwen van beton als monument wordt beschermd, moeten restauratiespecialisten nog kennis vergaren over de geschiedenis en eigenschappen van historisch beton. En hoewel er vaak over de historie van beton als constructiemateriaal gesproken wordt, is er weinig bekend over de samenstelling en afwerking van historisch beton.

Bij de restauratie van historische betonnen gebouwen worden, in het algemeen, de voor modern beton gangbare reparatietechnieken toegepast. Vanuit technisch oogpunt is het daaruit voortvloeiende resultaat soms teleurstellend, omdat de eigenschappen van historisch beton vaak afwijken van die van modern beton. Vanuit

restauratieoogpunt zijn er nog meer bedreigingen, omdat randvoorwaarden, zoals respect voor het historisch materiaal en voor cultuurhistorische waarden in het algemeen niet meegenomen worden bij het uitvoeren van reparaties. Door de reparatie van historisch beton uit te voeren zonder kritische blik en met een gebrek aan kennis groeit het risico van het verlies van historisch bewijs en historisch materiaal.

Daarom is het doel van dit proefschrift de ontwikkeling van een conservering technische aanpak, die de specifieke eigenschappen en de cultuurhistorische waarden van historisch beton respecteert.

De voornaamste onderzoeksvragen zijn daarom:

- Hoe kan historisch beton samen met zijn cultuurhistorische waarden worden geconserveerd?
- Hoe kan een voorgenomen restauratiestrategie worden beoordeeld op zijn gevolgen voor zowel de cultuurhistorische waarden als voor de technische prestatie?
- Hoe kunnen technische eisen en het behoud van cultuurhistorische waarden tegen elkaar worden afgewogen, wanneer de waarden enerzijds en de duurzaamheidsproblemen anderzijds zijn terug te voeren op dezelfde materiaal-technische achtergrond?

De opbouw van dit proefschrift weerspiegelt het oogmerk om een specifieke restauratiestrategie voor historisch beton te ontwikkelen.

Deel 1 - Het begrijpen en karakteriseren van historisch beton

Het eerste deel vormt een compendium voor historisch beton, waarin de ontwikkeling van ontwerpregels en voorschriften in Nederland aan de orde komt. In het bijzonder komen de bestanddelen (bindmiddel, toeslagmaterialen, water), samenstelling, wapening en afwerking aan bod. Dit deel wordt geïllustreerd met Nederlandse voorbeelden en geeft ondersteuning voor zowel technische als historische opname. Ook biedt de historische achtergrondinformatie voor diepergaand (materiaaltechnisch)onderzoek.

Deel II - Interpretatie en evaluatie van historisch beton

Het tweede deel vormt een gids voor het identificeren van risico's voor het materiaal en voor de cultuurhistorische waarden. Hierbij inbegrepen zijn methoden om de cultuurhistorische waarden aan het historisch beton en de staat van conservering te relateren. Bovendien zijn de voor- en nadelen van verschillende reparatietechnieken vanuit een restauratieperspectief geëvalueerd. Deze nieuwe aanpak wordt vervolgens toegepast op drie casussen: Fort Bezuiden Spaarndam (1897-1901), het Hofplein spoorwegviaduct (1900-1908, A.C.C.G. van Hemert), en de keermuren van het onvoltooide Groot Museum (1921, H. van der Velde).

Deel III - Ontwikkeling en evaluatie van een specifieke restauratiestrategie

In het afsluitende deel wordt gekeken naar de beslissingen die nodig zijn bij het ontwikkelen van een specifieke restauratiestrategie. De voorgestelde aanpak houdt rekening met het afwegen van het behoud van cultuurhistorische waarden enerzijds en de technische eisen anderzijds. Ook worden casusspecifieke criteria geformuleerd, die een beschrijving van potentiële restauratiestrategieën mogelijk maken.

Dit proefschrift presenteert nieuwe kennis over historisch beton, waarbij historische ontwikkelingen met materiaaleigenschappen worden gecombineerd. Verschillende perioden binnen de gebruiksduur van beton zijn met elkaar verbonden: het verleden, door de uitleg van mogelijke betekenis en duurzaamheid, het heden, door het evalueren van prestatie en staat van conservering, en de toekomst, door ondersteuning bij het nemen van beslissingen voor een geschikte restauratiestrategie.

Dit proefschrift streeft er nadrukkelijk naar om de noodzakelijke overgang van betonreparatie naar betonrestauratie te ondersteunen.

Delft, 2012 Herdis Heinemann

Contents

Acknowledgements	i
Summary	iii
Samenvatting	vii
1 Introduction	1
Chapter outline	1
1.1 Research motivation	1
1.2 Definitions and terminology	6
1.3 Review	10
1.3.1 Literature review	10
1.3.2 Review of Dutch concrete conservation practice	14
1.3.3 Identification of detail and scope of the thesis	20
1.4 Research objective	24
1.5 Approach	25
1.6 Thesis outline	26
 I Understanding and Characterisation of Historic Concrete	 29
2 Historic concrete in the Netherlands	33
Chapter outline	33
2.1 Introduction	33
2.2 Historical context	36
2.2.1 19 th century: from plain to reinforced concrete	37
2.2.2 Early 20 th century: exploration and dissemination	44
2.2.3 Interwar period: standardisation and professionalisation	48
2.2.4 Second World War and reconstruction: confidence and quantity	52
2.3 Historical context and material properties	54
2.4 Conclusions	55

3	Binders	61
	Chapter outline	61
3.1	Introduction	61
3.2	Development of binders used for historic concrete	62
3.3	Historic binders used in the Netherlands	65
3.4	Origin of cements used in the Netherlands	72
3.5	Quality and standardisation of cements used for historic concrete .	75
	3.5.1 Composition and durability	75
	3.5.2 Fineness of cement	77
	3.5.3 Introduction of standards	78
3.6	Portland cements	78
	3.6.1 Normal Portland cement	80
	3.6.2 Special Portland cement	83
	3.6.3 White cement	84
3.7	Natural cement (<i>Natuurcement</i>)	86
3.8	Slag-bearing cements (<i>Cementen met Hoogovenslakken</i>)	88
	3.8.1 <i>Slakkencement</i> (Slag-lime cement)	91
	3.8.2 <i>IJzerportlandcement</i> (Portland-slag cement)	92
	3.8.3 <i>Hoogovencement</i> (Blast furnace slag cement).	93
	3.8.4 <i>Gesulfateerd cement</i> (Supersulphated cement).	94
3.9	Pozzolanic cements	95
	3.9.1 Trass and trass bearing cements	96
	3.9.2 Fly ash cement (<i>Vliegas cement</i>)	101
3.10	Other cements	101
	3.10.1 <i>Erts cement</i> (Erz cement)	101
	3.10.2 <i>Aluminium cement</i> (High-aluminium cement)	102
3.11	Identification of the used binder	104
3.12	Conclusions	106
4	Aggregates	109
	Chapter outline	109
4.1	Introduction	109
4.2	Fine aggregates	112
4.3	Coarse aggregates	112
	4.3.1 Gravel (<i>Grind</i>)	118
	4.3.2 Crushed stone (<i>Steenslag</i>)	120
	4.3.3 Broken bricks (<i>Puin/brikken</i>)	121
	4.3.4 Aggregates for lightweight concrete	125
	4.3.5 Geometry of coarse aggregate	127
4.4	Grading of aggregates	131
4.5	Conclusions	135
5	Concrete mix design	139
	Chapter outline	139

5.1	Introduction	139
5.2	Cement content	141
5.3	Mixing water	147
5.3.1	Quality of the mixing water	147
5.3.2	Quantity of mixing water	148
5.4	Admixtures and additions	155
5.5	Conclusions	159
6	Reinforcement	161
	Chapter outline	161
6.1	Introduction	161
6.2	Application and history of reinforced concrete	164
6.2.1	Terminology of reinforced concrete	167
6.2.2	Terminology and composition of the used metals	169
6.2.3	Quality and classification of the used ferrous metals.	176
6.3	Geometry of reinforcement bars	180
6.3.1	Plain reinforcing bars	181
6.3.2	Standard profiles	182
6.3.3	Patented reinforcement bars	191
6.3.4	Cold worked twisted bars	194
6.3.5	Ribbed reinforcement bars	197
6.3.6	Welded wire meshes	197
6.4	Connection of the reinforcement	199
6.5	Concrete cover of the reinforcement	205
6.6	Conclusions	214
7	The surface finish of historic concrete	215
	Chapter outline	215
7.1	Introduction	215
7.2	The development of concrete surface finishes	219
7.3	Surface finishes applied to historic concrete	232
7.3.1	Rendering	233
7.3.2	Painting	238
7.3.3	Tooling	240
7.3.4	Sand blasting and washing out	245
7.3.5	Polishing and rubbing down	251
7.3.6	Metallised concrete	251
7.4	Formwork finishes	258
7.5	Constituents to colour concrete	271
7.5.1	Colour of the cement	271
7.5.2	Coloured aggregates	276
7.6	Facing concrete	282
7.7	Decorative concrete	286
7.8	Conclusions	290

II Interpretation and Evaluation of Historic Concrete 293

8 Mutual relationship between the heritage values, historic concrete and state of conservation	297
Chapter outline	297
8.1 Introduction	297
8.2 Categories of heritage values	299
8.3 Mutual relationship between heritage values and historic concrete .	303
8.4 Mutual relationship between heritage values and the state of conservation	310
8.4.1 Technical survey of historic concrete in practice	310
8.4.2 How to relate heritage values and the state of conservation	312
8.5 Fort Bezuiden Spaarndam (1897-1901)	318
8.6 Hofplein railway viaduct (1900-1908)	322
8.7 Earth retaining walls of the unfinished Groot Museum (1921) . . .	328
8.8 Conclusions	332
9 Impact of repairs on historic concrete and heritage values	333
Chapter outline	333
9.1 Introduction	333
9.2 Conservation or repair?	335
9.2.1 Repair	336
9.2.2 Conservation	336
9.3 General requirements towards repair techniques	340
9.3.1 Compatibility	340
9.3.2 Retreatability and reversibility	343
9.3.3 Durability	344
9.3.4 Heritage service life	345
9.4 Repair techniques	347
9.4.1 Concrete removal	347
9.4.2 Repair mortars	351
9.4.3 Concrete injection	362
9.4.4 Surface treatments	363
9.4.5 Electrochemical repair techniques	369
9.4.6 External strengthening	377
9.5 Conclusion	377

III Development and Evaluation of a Dedicated Conservation Strategy 381

10 Development of the conservation aim	385
Chapter outline	385
10.1 Introduction	385

10.2 Four different states of the historic concrete	386
10.2.1 Actual state of conservation	387
10.2.2 Ideal state	388
10.2.3 Expected state of conservation	389
10.2.4 Acceptable state of conservation	391
10.2.5 Relationship between the four different states and conserva- tion aim	391
10.3 Fort Bezuiden Spaarndam (1897-1901)	393
10.4 Hofplein railway viaduct (1900-1908)	395
10.5 Earth retaining walls of the unfinished Groot Museum (1921) . . .	396
10.6 Conclusion	398
11 Development of a dedicated conservation strategy	401
Chapter outline	401
11.1 Introduction	401
11.2 Criteria for a dedicated conservation strategy	402
11.3 Evaluation of different conservation strategies	404
11.4 Fort Bezuiden Spaarndam (1897-1901)	407
11.4.1 Preservation of the original concrete and paint	407
11.4.2 Conclusions Fort Bezuiden Spaarndam	413
11.5 Conclusions	415
12 Conclusions and recommendations	417
12.1 Scientific results	417
12.1.1 Identification of problems	417
12.1.2 Reflecting the research questions	420
12.1.3 Discussion of results	425
12.2 Further research and recommendations	430
12.3 Final conclusions	431
IV Appendices	433
A Obsolete concrete terminology (English, Dutch, German)	435
B Overview of visited objects	443
C Overview of the different editions of the G.B.V.	453
D Overview of the historic concrete mixtures described in Dutch textbooks.	471
E Pigments used for historic concrete	475
Bibliography	479

Standards	511
List of symbols and abbreviations	515
List of Figures	516
List of Tables	532
Curriculum-vitae	535

Chapter 1

Introduction

Chapter outline

In this introductory chapter, the framework of this research will be explained. The research topic - conservation of historic concrete - will be introduced. The motivation for this research will be described, the term *historic concrete* defined, and the research questions posed. The specifications of this thesis regarding the intended user groups are formulated and the approach discussed. The chapter concludes with the thesis outline.

1.1 Research motivation

Both plain concrete and reinforced concrete have significantly changed the design and properties of buildings and structures over the last 150 years. In present day building construction, the use of (reinforced) concrete is omnipresent and concrete is worldwide the main construction material. In the Netherlands, the annual concrete production is currently 14.5 million m³; in 2000, the annual production of cement, a main constituent of concrete, reached a new record of 6.25 million tonnes (Cement & Beton Centrum, 2012a,b). In 1920, a period in which reinforced concrete slowly became accepted as a common building material, the annual sales of cement were 0.374 million tonnes; in 1948, during the reconstruction period after the Second World War, it reached 1.2 million tonnes (Mos, 1949).

These numbers not only indicate an increase of cement use of nearly 1700% in 90 years. Hidden in them are technological developments, the struggle of accepting concrete as a building material and the explorations of the structural and aesthetical possibilities of concrete. Hidden as well are the trials and errors of the pioneers, exploring a new material. Hidden are the details and evidence of the construction and material history of concrete in the Netherlands.

In addition to being the world's main construction material, concrete is gaining more importance as a historic building material, representing the major changes in construction methods in the late 19th and 20th century.

Many motives exist for the interest in the history of (construction) materials. It is sometimes a passion of engineers curious of the origin of their profession and field; the repair and conservation of existing buildings is another motive, as former construction methods and materials used can vary from present day approaches.

Until recently, the treatment of degraded concrete structures was the domain of concrete repair, both research and industry. Yet, in the last decades, heritage care authorities and historians became more interested in the field. With the increasing distance to structures and buildings dating from the second half of the 19th century and early 20th century, these were reviewed for their historical significance. Another motivation for research was often the threat of demolition or on-going deterioration of former iconic buildings (Figure 1.1).

Compared to previous periods, buildings and structures from this period showed novelties in design, typology, construction methods, enabled with new materials such as iron and reinforced concrete. Parallel, the increasing education of military and civil engineers supported dissemination of new technologies and design methods. The development of materials and design shifted from empiric approaches to scientifically based findings. The application of innovative materials and structural design were not only limited to military and civil structures, but influenced architecture as well.

In the Netherlands, this period has previously been investigated by the *Rijksdienst voor de Monumentenzorg* (RDMZ, Dutch Cultural Heritage Agency).¹ From the late 1980s to early 1990s, the *Monumenten Inventarisatie Project* (MIP, Monuments Inventory Project) was carried out, aiming at establishing an inventory of Dutch buildings and town planning from between 1850 and 1940 (see for example RDMZ, 1991; Van Oudheusden, 1992a,b). One result of this inventory was that an increasing number of buildings dating from this period was listed as monuments. In a follow-up project, the reconstruction period during and after the Second World War (*Wederopbouw periode*, 1940-1965) was evaluated, leading to the suggestion of 100 representative buildings for listing dating from 1940-1958 in 2007.²

Parallel to an urban and architectural inventory, investigations of the changes in construction method and material use were initiated by the RDMZ. As the

¹The Dutch Cultural Heritage Agency *Rijksdienst voor de Monumentenzorg* (RDMZ) changed in 2006 its name into *Rijksdienst voor Archeologie, Cultuurlandschap en Monumenten* (RACM), and in 2009 into *Rijksdienst voor het Cultureel Erfgoed* (RCE).

²In the Netherlands, two grades of listing exist: as *rijksmonument* (national monument), which is the highest grading, and as *gemeentelijk monument* (local authority monument). In some provinces, the grading as *provinciaal monument* (provincial monuments) is possible. In order to be listed as a *rijksmonument*, the minimum age of a building was 50 years according to the *Monumentenwet* 1988 (heritage act) (Ministerie voor Onderwijs Cultuur en Wetenschap, 1988). On January 1st, 2012, this threshold was abolished, yet at the same time, the listing of buildings as *rijksmonument* in general was abolished as well (RCE, 2012). The listing of younger building was and still is possible as a *gemeentelijk monument*.



(a)



(b)

Figure 1.1 Example of a deteriorated architectural icon, the Dresselhuys pavilion, part of the former Sanatorium Zonnestraal (Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928, situation 2008). Details of the concrete staircase after years of neglect just before repair, showing typical degradation symptoms such as detachment of render, biological growth, spalling and corrosion. a) Roof of the staircase. b) Stringer of the staircase.

former RDMZ director Van Nispen tot Sevenaar stated, the period was not only characterised by new architectural styles but also by changes in structure and use of new materials (Oosterhoff, Arends, van Eldik & Nieuwmeijer, 1988, p. IX). Research was initiated on new construction materials, namely iron and concrete, and their application (for example, Kuipers, 1987; Oosterhoff, 1998; Oosterhoff et al., 1988; Stokroos, 1985).

As a consequence of the listing of buildings dating from the 19th and 20th century, the question arose of how to protect them. One aspect was to create sound descriptions of the buildings and determine their heritage value. Another question also arose: How to technically implement the demands of protection and preservation? In this context of exploring the history of early 20th century architecture and their preservation, *Docomomo International* (DOcumentation and COnservation of buildings, sites and neighbourhoods of the MODern MOVement) was founded in 1988, a non-profit organisation of Dutch origin, focussing on the ideas and heritage of the Modern Movement (in Dutch *het Nieuwe Bouwen*).

The review of 20th century architecture as part of the built heritage was not only a Dutch phenomenon, but occurred in several countries; it was also addressed by *ICOMOS International Council on Monuments and Sites* which installed an *International Scientific Committee on 20th Century Heritage*. Discussion was initiated whether existing methods for selection and conservation were applicable to the new categories of monuments, especially for buildings from the 1920s onwards associated to the Modern Movement and of the post-war reconstruction period (for example Cunningham, 1998; Macdonald, 1996, 2001; Prudon, 2008).

Arguments for a different approach were the increasing influence of the architect and the often iconic character of the buildings, favouring the reconstruction of the original design intent, rather than preserving the actual state of a building with present modifications. Changed production methods and increased prefabrication questioned the significance of workmanship and original material as it is done for more traditional buildings. Failure of new construction materials, which were applied with limited insight into their durability, caused problems for repair and conservation. However, detailed material investigations to verify these arguments were not carried out.

Remarkably, a multidisciplinary discussion of the use of new construction materials for civil, military, architectural and artistic purposes was and still is seldom carried out; instead, historic concrete is mainly seen as an object facilitating new (architectural) designs. Approached as an object, the investigation and conservation of historic concrete is considered a secondary task, necessary to preserve an iconic building or structure. A critical review whether or not the historic concrete itself is a historic entity demanding investigation and preservation, especially in the context of its technological development, is rarely undertaken.

Parallel to the academic discussion, practical questions became also relevant. Interventions were required, as many historic concrete buildings suffered from years of vacancy and neglect, or vacant industrial buildings were transformed into housing and office buildings (Figure 1.2). The need for local knowledge dissemination



Figure 1.2 Example of the conversion of a former factory into an office building (Van Nelle factory, J.A. Brinkman and L.C. van der Vlugt, 1926-1931, situation 2006).

was acknowledged: publications and leaflets were distributed, introducing the conservation field into the principles of degradation and repair of concrete (De Jonge & Doolaar, 1997; Henket & De Jonge, 1990; RDMZ, 2004; 2006a; 2006b). In 2006, the *Rijksdienst voor Archeologie, Cultuurlandschap en Monumenten* (RACM) organised a symposium to address the topic of concrete conservation to a wider audience, focusing on the basics of concrete history, degradation mechanisms and repair techniques (RACM, 2006).

In the last decades, the conservation of concrete has become an increasingly important task for heritage care agencies, not only in the Netherlands but internationally. Case studies of conservation projects, often of iconic buildings, are frequently published. Yet common shortcomings are the lack of detailed information on the properties of the historic concrete and of a critical review whether the repair methods applied are suitable for conservation. In addition, when visiting buildings several years after conservation, observing premature failure of interventions is not uncommon. From the cases studied during this research, similar observations were made: conservation demands are seldom implemented during the planning and execution of repair works, raising the question whether there is an underlying technical or methodological reason, or a combination of both.

In this thesis, the fundamental aspects regarding the characteristics of historic concrete and the way of its conservation are elaborated. Conclusions are drawn on how we can improve our current practice in order to achieve a dedicated conservation strategy for historic concrete. The focus of this thesis lies on the historic concrete itself, as interactions between the three aspects - heritage values, degradation and intervention - take place through the historic material (see Figure 1.3).

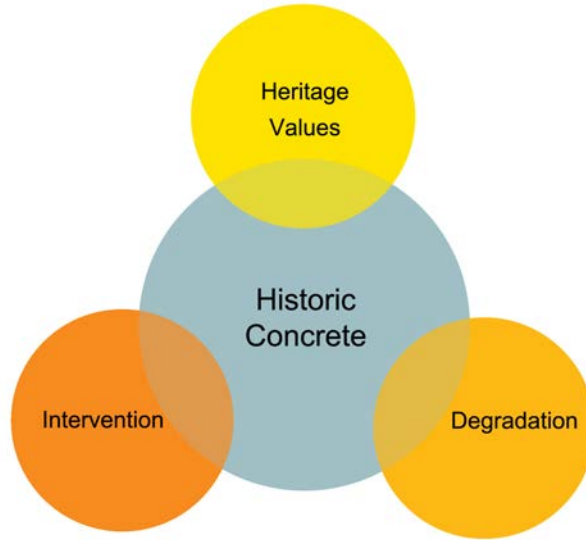


Figure 1.3 Schematic drawing of the relationship between heritage values, degradation and interventions.

1.2 Definitions and terminology

Before discussing the details of historic concrete, it is necessary to define historic concrete as used in this thesis. Concrete is a composite material, and small differences in perception can be noticed during time. The present day definition of concrete is a *“material formed by mixing cement, coarse and fine aggregates and water, with or without the incorporation of admixtures and additions, which develops its properties by hydration of the cement”* (NEN-EN 206-1:2005). This corresponds in principal to the historic composition of concrete: cement, aggregates and water. However, historically cement was also used as a synonym for binders, and included hydraulic lime, whereas in the present day standard NEN-EN 197-1:2011 *Cement*, hydraulic lime is not considered as a cement.

It is still discussed when, where and by which culture concrete was invented; the proposed answers are influenced by the definition of concrete. When defining it as a lime or gypsum binder used to bond natural stones or bricks, the origin is considered to be in the ancient civilisations such as Mesopotamia, ancient Egypt or Greece (Jahren, 2011; Scharroo, 1946; Sinn, 1973). When understanding concrete as a composite material made from hydraulic binders and aggregates, and poured in a formwork on-site, the concrete used by the Romans is considered as most relevant in terms of influence in a European context (Lamprecht, 1987; Malinowski,

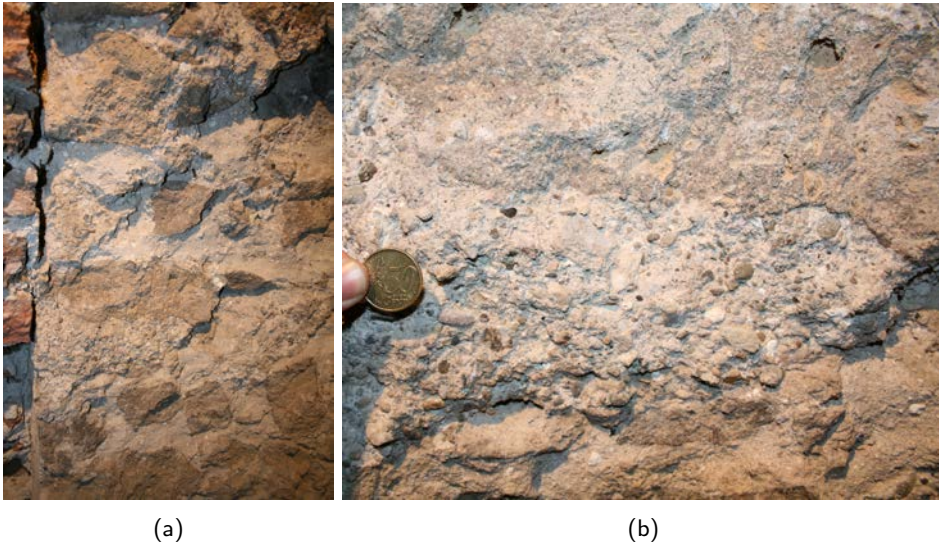


Figure 1.4 Details of the remains of a former Roman Castellum in Utrecht. a) Overview showing the use of large coarse aggregates. b) Close-up of the mortar.

1979). The main aspect would be hereby the knowledge dissemination with the expansion of the Roman Empire.

The Romans are considered the first to apply concrete, *opus caementicium*, on a wide scale. *Opus caementicium* was not only a material but also a construction technique and referred to pouring of aggregates and a binder between a timber formwork or brick walls. The conglomerate was made of broken bricks, rocks, hydraulic or non-hydraulic binders, optional pozzolana, ground brick, or trass (depending on the geographical region) and water (Huberti, 1964; Lamprecht, 1987; Scharroo, 1946). With the decline of the Roman Empire, the use of *opus caementicium* decreased but the knowledge to manufacture binders and bricks remained locally. With the survival of the knowledge, the terminology, although altered, survived as well.

The origin of the word cement can be traced back to *caementum*, which originally referred to the aggregates used in *opus caementicium*. The changing meaning of the word can be identified in the double use of bricks: on one hand as aggregates, on the other hand when finely ground as a latent hydraulic additive. Ground brick was still used for centuries as an additive for binders, and together with trass, another latent hydraulic binder made from tuff stone, these were called cement (Huberti, 1964; Oxford English Dictionary, 2012b). Roman concrete will not be further discussed in this thesis, as the historical context and material properties vary strongly from the concrete used since the 19th century. In addition, only few remains of Roman concrete exist in the Netherlands (Figure 1.4), which are mainly of archeological interest.

The term **concrete** is of Latin origin as well: *concrecere*, meaning growing together. Its use for a composite of aggregates and binder for construction purposes is known since the first half of the 19th century (Oxford English Dictionary, 2012c). The origin of the French term *béton* is more discussed. It is assumed that it is a development of the Latin *bitumen*, meaning mineral pitch, or of the old French word *betun*, meaning rubble, mud (Huberti, 1964; Oxford English Dictionary, 2012a). In 1618, the French J. Martin translated Vitruvius works, using the term *bétum* for Roman concrete. In 1818, the French B. F. de Bélidor (1697 - 1761) was the first to introduce the term *béton* with his publication *Architecture hydraulique* (published in four volumes between 1737-53, De Bélidor). *Béton* referred here to a mix of hydraulic mortar with coarse aggregates (Huberti, 1964; Ramm, 2007). The idea of concrete as a mix of a mortar with coarse aggregates remained common for the next century (for example Becker, 1857; Storm van 's Gravenzande, 1850, 1863). The German obsolete term for concrete *Grobmörtel* (coarse mortar) reflects this concept (Becker, 1857; Van der Kloes, 1908c).

Early discussions on the definition of concrete include the type of binder used. The English term *concrete* could refer to the use of quicklime and pouring the concrete when still warm (Storm van 's Gravenzande, 1850, 1863), whereas the French term *béton* could refer to the use of slaked lime (Reid, 1869; Vicat, 1837). These terms could be used parallelly, even in English literature, whereas in general preference for one term developed. In the Netherlands, Germany and the Scandinavian countries, the French term *béton* became common and in England concrete. Concrete was then defined as a “*mass held or bound together by an agent of cementation of varied character and quality*” (Reid, 1879).

Reinforced concrete is a composite material, made of concrete and an embedded reinforcement. The structural advantage of reinforced concrete is that the reinforcement carries the tensile stresses and the concrete the compressive loads. Different materials can be used as reinforcement, although most commonly used is steel. The terminology for reinforced concrete varied over time, mainly influenced by different early patent holders for reinforcement systems. In the Netherlands, French and German influences can be noticed before a consensus was reached on the term *gewapend beton* in the 1910s. The use of the different obsolete Dutch terms (*cementijzer*, *betonijzer*) will be discussed in Chapter 6.2.1 *Terminology of reinforced concrete*.

In this thesis, present day English terminology will be used: concrete and reinforced concrete, and plain concrete for structural concrete without an embedded reinforcement. If a direct translation of Dutch terms is not possible due to differences in connotation, the Dutch term will be used and an English approximation given. This is especially necessary for the different constituents used for concrete. In Appendix A, an overview is given of obsolete Dutch, English and German terminology, which can be consulted when reading this thesis or when working with historic documents.

In addition, it has to be distinguished between concrete as used in current practice and concrete encountered in historic buildings. In this thesis, a differentiation is made based on both the period of application and the deviating properties of modern and historic concrete. Concrete dating from the 19th century until the late 1960s will be discussed in this thesis and further on described as historic concrete. The starting point of the investigated period corresponds with the introduction of concrete in the Netherlands; the end is based on both material characteristics and recent developments within the Dutch heritage care (see Section 1.1).

In terms of heritage policy, the investigated period coincides with two periods within Dutch heritage care, the so-called *Jongere Bouwkunst* (Young architecture, 1850-1940) and *Wederopbouw* (Post-World War II reconstruction period, 1940-1965). Until now, most historical research was limited to the period before 1940 (for example Blijstra, 1973; Disco, 1990; Kuipers, 1987; Oosterhoff, 1998; Oosterhoff et al., 1988; RDMZ 1991; Van Maarschalkerwaard, 1996; Van Oudheusden, 1992a,b). The architectural and technological changes after 1940 have been only addressed recently (e.g. Zijlstra, 2009). Detailed construction and material historical research is still lacking for both periods. In case of historic concrete, significant material developments and aesthetical explorations still took place in the decades after World War II.

From a technical and architectural point of view, the main challenges regarding the acceptance of concrete as a building material and technological progress had taken place by the 1960s. This includes the quality control of raw materials, the understanding of the properties of concrete, and methods of design and construction. The basics of concrete durability were understood and slowly implemented, and confidence existed in the late 1960s of using concrete on a large scale. The infrastructure for such a large scale application existed by the late 1960s, including concrete construction companies, material suppliers, and engineers and workers trained for reinforced concrete. Standards changed as well; the concept of the *Ge wapend Betonvoorschriften* (G.B.V., Netherlands Code of Practice for Reinforced Concrete) was systematically changed and extended with the introduction of the *Voorschriften Beton VB 1974* (Netherlands Code of Practice for Concrete). In addition, national characteristics in terms of material use and design codes were slowly reduced with the development and introduction of European standards from the 1970s onwards. The decline of the popularity of concrete in the 1970s as an architectural material, in combination with problems in terms of building physics and durability associated with concrete buildings, can be seen as the end of the first phase of enthusiasm for the use of concrete. Moreover, the Post-War (re)construction boom had diminished by the 1970s.

The progress of concrete development did not end in the 1960s; research on the improvement and understanding of concrete and development of new constituents still goes on, and new requirements exist such as sustainability and increased durability. Yet from an early 21st century perspective, insufficient time has elapsed to evaluate the achievements of the last decades. A critical review of the present and recent history of concrete has to be the task of the following generations.

1.3 Review

To understand the current challenges of concrete conservation, it was necessary to review both knowledge and practice. Section 1.3.1 reviews the state-of-art regarding knowledge of historic concrete and its conservation, and knowledge dissemination towards practitioners. Section 1.3.2 reviews the current practice of concrete conservation, focusing on the decision-making, the available references and expertise, and the relationship between the involved disciplines. The review presented in Section 1.3.3 aims at identifying the specific requirements for this thesis, considering the intended user groups and the level of sophistication of the field, as this determines the level of detail of this research.

1.3.1 Literature review

For conservation, information on suitable techniques and methods is necessary. As conservation of historic concrete is rather recent when compared to traditional materials such as brick or natural stone, the question arises whether the current level of sophistication and detail of existing reference works is sufficient. More fundamental is the question related to current knowledge and research gaps.

Reviewing the current knowledge on historic concrete and its conservation in the Netherlands reveals that only a few important publications exist which focus on historical concrete. These, however, prioritise the social and historical context of specific case studies or typologies. For the innovative use of different concrete building systems for social housing in the Interwar period, Kuiper's (1987) thesis can be consulted; Oosterhoff et al. (1988) are the first to give an overview of structural design in reinforced concrete, Oosterhoff (1998) more specifically on its use for bridges. In an overview of the development of construction of the forts of the Stelling van Amsterdam (Defense Line of Amsterdam), the use of plain concrete for military buildings is briefly addressed (Vesters, 2003).

The Dutch history of cement, namely its invention and production are discussed in Heerding (1971), focusing on the history of the companies *Eerste Nederlandse Cement Industrie* (ENCI, First Dutch Cement Industry) and *Cement Industrie IJmuiden* (CEMIJ, Cement Industry IJmuiden), and in Felder (2006), addressing early production attempts in the province of Limburg. In their theses, Disco (1990) and Deuten (2003) describe the emerging of concrete technology; Disco focusing on the role of civil engineers and Deuten on knowledge dissemination.

Pieter Wilhelmus Scharroo's (1883-1963) historical review "*Cement en beton - Oud en Nieuw*" (Cement and concrete - Old and new) from 1946 is still used in practice as the main reference for the history of concrete in the Netherlands. Scharroo was a military engineer and an eyewitness of the early years of concrete application in the Netherlands. His work is thus highly valuable and gives a broad overview of former and often forgotten materials used in concrete. However, as the book was published nearly 70 years ago, it obviously neither covers developments after the Second World War nor considers later insight into concrete technology

and durability. The work of Scharroo is therefore an important historic handbook for concrete construction history until the 1940s. Nevertheless, the work lacks a critical review of the success and failures of concrete technology and techniques, an important aspect when considering the durability of historic concrete structures. Bot's (2009) more recent reference work on different historic building materials can be used as a first orientation although caution has to be exercised as occasionally incorrect terminology is used and material details inaccurately described.

As these publications are historical reviews, they mainly investigate the historical context using historic documents. They seldom relate to the present day situation of the buildings nor identify the described material properties and the consequences for conservation, such as durability issues or requirements for compatible conservation techniques. Another limitation is that most publications only investigate the period until 1940, which was valid nearly 25 years ago when most were written. However, buildings from the reconstruction period after the Second World War are now listed as monuments. As significant changes in application and technology took place in this period, additional information is required.

The publication of monographs of iconic and listed concrete buildings, which underwent either conservation or transformation, is common practice. Examples of extensive monographs are about the restoration of the Zonnestraal Sanatorium (Figure 1.5, Meurs & van Thoor, 2011), the Van Nelle Factory (Figure 1.2, Backer, Camp & Dicke, 2005), and other, smaller publications about the industrial buildings De Witte Dame (Ferril, 1998), Mercurius (Figure 1.6, Goudeau, 1997) or Radio Kootwijk (Figure 1.7, Spits, 2008). In general, the emphasis lies on the historical context of the original design and architectural intention, biographical information of the main architects or engineers, and discussion on the re-use and policies. Detailed information on the construction and material history, the encountered degradation and executed repairs is usually not given; if given, it mainly focuses on the structural design (e.g. mushroom floors) or new façade types. A critical review of the technical challenges and chosen intervention regarding the historic concrete, and information of the long-term performance of the repair is not present.

Reinforced concrete is considered to be an international material. The historically used design theories, principles of material composition and construction methods are thus comparable in different countries. Especially the history of (reinforced) concrete in France, Germany and Great Britain is frequently discussed. Great Britain is often mentioned in context with the development of new cements, especially of Portland cement; France is seen as the cradle of reinforced concrete and Germany mentioned for its scientific approach towards cement production and design theories. For the Dutch context, foreign reference works can and should be consulted to understand the historical context and details of foreign systems. However, it has to be taken into account that not all new materials and new reinforcement systems had to have been applied in the Netherlands, and if so application could have been delayed. In addition, it has to be considered that often local materials, especially aggregates, were used, and that national codes of practice, if present, could have resulted in different designs and material use.



Figure 1.5 Former Sanatorium Zonnestraal (Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928, situation 2008).



Figure 1.6 Former storehouse Mercurius, which was transformed into an office building (Wormerveer, M. J. Stam, 1919, situation 2006).



Figure 1.7 Former radio station Kootwijk (J. M. Luthmann, J. Emmen, 1921-22, situation 2006).

Reviewing foreign literature for the state of knowledge of historic concrete, it is noticeable that detailed material information is scarce (for example Addis, 2007; Collins, 1959; Curbach, van Stripriaan, Wachtendorf & Wiens, 2007; Huberti, 1964; Newby, 2001; Simonnet, 2005; Yeomans, 1997). Main topics in these publications are the evolution of different reinforcement systems, including peculiarities of calculation and inventor, the advances in cement development and production, initially leading construction companies and iconic buildings and structures.

With the increasing demand to re-use historic concrete buildings and structures, background information for structural evaluation and recalculation is published (for example Clarke, 2004; Fingerloos, 2009; RBBK commissie, 2004; Sutherland, Humm & Chrimes, 2001). In these works, the differences in design codes are discussed (e.g. calculation of shear forces, applied safety factors), former quality classes converted into present day classes, and guidance given for the recalculation using contemporary knowledge on mechanics and safety.

Information on the durability and deviating properties of historic concrete can occasionally be found in (present day) concrete textbooks (for example Bogue, 1947; Stark & Wicht, 2001). Anecdotes on the discovery of new damage mechanisms, exemplary historic cases of degraded concrete buildings, and resulting research and changing composition of concrete and cements material are sometimes discussed.

In the last years, case studies of the repair of historic concrete are published more frequently in technical journals and concrete repair proceedings (for example Bertolini, Bolzoni, Cigada, Pastore & Pedferri, 1993; Bertolini, Carsana, Gastaldi, Lollini & Redaelli, 2011; Bertolini, Carsana & Redaelli, 2008; Drewett & Bott, 2011; Grantham, 2011b; Mezzina, Palmisano & Uva, 2010; Redaelli & Bertolini, 2011; Williams, 2008). The main topics are their structural assessment, methods of material characterisation, and challenges of repair.

Some publications address specifically the conservation of historic concrete, including historical and technical aspects, and case studies (see for example De Jonge & Doolaar, 1997; Hassler, 2010; Hassler & Schmidt, 2004; IFS, 2004, 2008; Macdonald, 2003; Müller, Nolting, Vogel & Haist, 2004; RACM, 2006; Sutherland et al., 2001). As most books are a compilation of individual researches and case studies, they are often fragmental and address in detail neither the periods and properties of historic concrete nor the challenges for conservation. Guidelines for the conservation of historic concrete (Gaudette & Slaton, 2007; Reed, Schoonees & Salmond, 2008) try to give a generic overview of repair options and special material characteristics. Detailed information, which could give guidance for a specific conservation project is however not provided.

In general, existing publications focus mainly on iconic buildings and structures, or address historic key figures or moments. Generic information reflecting of the use and properties of historic concrete in different periods is not available. Remarkable is the fact that plain concrete is seldom mentioned, although plain concrete structures were common in the 19th century.

A common phenomenon in the mentioned publications is that historical aspects are separated from technical aspects. The correlation between previous material choices, construction methods, actual state of conservation and choices of conservation techniques is not discussed. The impression is given that conservation of historic concrete is mainly a challenge in terms of carrying out aesthetical compatible repairs, and resurrection of badly deteriorated structures. The principal aims of conservation, with the preservation of heritage values and respectful treatment of historic fabric, are seldom addressed, and if so, only in a conceptual manner but not worked out into technical implementation. The differences between modern and historic concrete and, between repair and conservation approaches are neither mentioned nor suggested.

1.3.2 Review of Dutch concrete conservation practice

Parallel to a literature review, a review of concrete conservation practice was carried out during an initial, exploratory phase. The motivation was to identify the achievements and obstacles of concrete conservation practice, as the reviewed literature did not reflect it sufficiently. The aim of the exploratory phase was to define the research questions and to better understand the field of concrete conservation. In addition to a literature study and the visit of several historic concrete buildings (see Appendix B *Overview of visited objects*), it was decided

to carry out two exploratory case studies, Fort Bezuiden Spaarndam (1897-1901) and Parksluizen Pumping Station (1968).³

As first case study, Fort Bezuiden Spaarndam, part of the Stelling van Amsterdam (Defence Line of Amsterdam, see Figure 1.8) was chosen.⁴ It was built in 1901 as a plain concrete structure. The building is a *gemeentelijk monument* (municipal monument) and, as part of the Stelling van Amsterdam, a UNESCO World Heritage Site. The interesting aspects of this case study were that it dates from the pioneering phase of concrete technology, and represents a period when the development of concrete was strongly driven/influenced by military institutions. The Stelling van Amsterdam was listed as a world heritage site not only for its military historical relevance, but also for its relevance for construction history, especially the transition from plain to reinforced concrete (ICOMOS 1996).

A large-scale conservation campaign started in 1997, with the intention to achieve a “role model” for conservation, as other forts needed conservation in the near future. As the works were carried out nearly 10 years ago, the mid-term performance of the conservation could be partially evaluated.

During a site visit in 2006, it was striking that the interventions were very invasive and after less than 10 years showed significant signs of failure (Figure 1.8b). The causes for the premature failure were mainly lack of experience with the degradation mechanisms and properties of early plain concrete. One of the main aims of the conservation campaign was to treat active cracks, which appeared due to the absence of expansion joints. The chosen approach was to create new expansion joints and fill the existing cracks. The execution of the repair was difficult (e.g. voids and interstices complicated the injection of cracks) and the new expansion joints were empirically dimensioned. During the site visit, it was noticed that the cracks had reappeared.

A second point was the visual impact of the repaired cracks. The crack pattern became very visible as the cracks were filled with a lighter coloured mortar than the surrounding concrete. During a closer investigation of the surface, several greenish spots were identified (Figure 1.8c). These were most likely remains of a previous camouflage paint layer, which was not documented and partially destroyed while cleaning the façade during the conservation. Additionally, in the original technical survey of the historic concrete, specific characteristics of early concrete concerning the binder and used aggregate were not identified.

For this case study, the restoration architect, the concrete repair company, and

³The research archives of the cases Fort Bezuiden Spaarndam and Parksluizen Pumping Station were destroyed during the fire of the Faculty of Architecture, May 13th 2008. Amongst the losses were original material samples and original documents such as technical surveys, but also notes from the interviews carried out with the involved parties. Where possible, it was tried to recover the lost information, in other cases secondary sources such as own papers had to be referred to for further research (for example Heinemann, 2007, 2008c; Heinemann, van Hees & Nijland, 2008).

⁴More detailed information on Fort Bezuiden Spaarndam regarding the conservation campaign and the construction history will be given in Sections 8.5, 10.3 and 11.4.



(a)



(b)

(c)

Figure 1.8 Pictures of the first case study Fort Bezuiden Spaarndam, part of the Stelling van Amsterdam (Defense Line of Amsterdam) (1897-1901, intervention 1998, situation 2006). a) Overview gorge façade. b) Detail of a failing crack repair and of newly created expansion joint. c) Detail of the façade showing remains of a presumably original green camouflage paint.

the concrete surveyor were interviewed.⁵ The major insight from these interviews was that none of the involved parties had experience with and knowledge of historic concrete. The choice of the repair materials and techniques was made from a concrete repair perspective. Possible heritage values ascribed to the building and the historic concrete were not further considered; any specific properties of historic concrete, which could have influenced the feasibility of a repair were not known.

Complementary to the first case study, publications related to the restoration of the fort, literature about the defence line and concrete of the beginning of the 20th century were studied (Bakker, 1996; Bureau Monumenten & Archeologie Haarlem, 1998; Gaasbeek, 2003; Gerritsen, 1995; Goudeau, 1992; Provincie Noord-Holland, 1996, 1998; Vesters, 2003). A conclusion of this pilot case study was that the premature failure of the repair was not primarily a technical problem but a problem of recognising and understanding historic concrete. In addition, heritage values or specific conservation demands were not taken into account (see also Heinemann et al., 2008).

The second case study was the pumping station Parksluizen in Rotterdam (1968, see Figure 1.9) by J. G. van der Grinten (born 1927) and H. J. Heijdenrijk (1932-1999). One main criterion for selecting this building was that it represented a different period of concrete use, i.e. late Post-war years, and the aesthetical and architectural use of exposed concrete. The use of reinforced concrete for structural elements had become common by then, and the aesthetical possibilities of concrete were widely explored.

This case reflects a common dilemma for buildings dating from this period, where corrosion has to be treated while fulfilling high aesthetical demands. The history of damage and repair of the pumping station is representative for many buildings. Several small scale standard repairs had been carried out during the years, not solving the problem and rather creating a patchwork look. The underlying cause of damage was an insufficient thickness of the cover concrete, aggravated by textural variations of the surface (see Figures 1.9b and 1.9c). Insufficient thickness of the concrete cover is commonly encountered at buildings from the period, facilitating corrosion induced by carbonation, and resulting in cracking and spalling of the exposed concrete.

In 1994, a large-scale repair campaign was started, but a standard repair approach was rejected by the authorities. Instead, an aesthetical compatible repair was demanded without removing or covering the present soiling, which was considered as an appreciable sign of ageing (Hinterthür, 1997; Van der Zanden, 1997). Several try-outs were made to find an aesthetical compatible repair mortar (texture, aggregate size and colour) and a matt coating to prevent further carbonation.

⁵As the conservation of Fort Bezuiden Spaarndam was an innovative project with little reference projects for the involved parties and heritage care institutes to consult, errors in judgement of the complexity of the intervention and of the feasibility of the chosen techniques are comprehensible. The encountered problems were not mainly related to a person or profession group, but to a general problem in the field. I would like to thank the interviewed parties for their openness to share their experience with me.



(a)



(b)



(c)

Figure 1.9 Pictures of the second case study, Parksluizen Pumping Station Rotterdam (J. G. van der Grinten, H. J. Heijdenrijk, 1968, repair 1996, situation 2006). a) Overview. b) Detail of exposed concrete stairs, showing the geometrical variations of the exposed concrete wall. c) Detail of a patch repair; gravel was added to adapt the texture to the surrounding eroded concrete; the repair mortar is greyer than the original concrete.

The results of the interventions were considered aesthetically acceptable, although one can notice the coating and the patch repairs (Figure 1.9c). The cause of the degradation has not been eliminated - insufficient concrete cover due to the geometrical design of the façade - and corrosion and spalling continue. In this case, a technical solution which would treat the cause of damage would have been possible. Instead, it was decided to put the emphasis on the appearance of the repair, and the technical performance and durability of the intervention were considered secondary. Measures to compensate the reduced durability of the intervention were not taken, such as retreatment of the coating in regular intervals.

Based on a cross-analysis of the two cases, and supported by interviews with different experts and a literature review (Section 1.3.1), the following preliminary conclusions were drawn on the underlying problem of concrete conservation:

- No specific concrete conservation techniques exist, in practice concrete conservation relies on concrete repair techniques and experts.
- Concrete repair aims differ from conservation aims.
- Interventions often put emphasis on one single aspect, either on a technical solution or on one category of values (mainly related to aesthetics), without considering the consequences for both the historic material and the heritage values.
- The properties and heritage values of historic concrete are not fully understood.
- Dilemmas often occur when aiming to preserve an “insufficiently durable” material or design.

In addition to the two explorative case studies, an investigation of the conservation process of several *rijksmonumenten* (national monuments) which had recently been granted subsidies was requested by the *Rijksdienst voor het Cultureel Erfgoed* (RCE).⁶ Similar conclusions were drawn as for the previously investigated cases. Furthermore, limited knowledge on the properties and history of historic concrete, its characterisation, problems with obsolete terminology and understanding of the historical context were identified.

The results of this review are used to formulate the research questions and define of the research objective, which will be introduced in Section 1.4 *Research objective*.

⁶Investigated were, amongst others, the conservation / historical research of the *Ambachtsschool* (Vocational School) in Zwolle (A. Baart & L. Krook, 1934), the industrial building Strijp-S in Eindhoven (J. R. Bouten, 1928 -1930), the Cenacle Church in Heilig Land Stichting (J. Stuyt, J. Margry, J. G. Wiebenga, 1913-1915), circumambulation passageway of the Pilgrimage church in Brielle (1912), and the Fortification Hellevoetsluis, built from 1880 onwards.

1.3.3 Identification of detail and scope of the thesis

As a preparatory work to identify the required level of detail and scope of the thesis, selected methods and guidelines used either for conservation or for concrete repair were reviewed. The motivation was to identify the thesis' requirements regarding the level of detail, the intended user groups, and the influence of the level of sophistication of both the research field and user groups. The criteria for selection were that methods and guidelines were related to either conservation or repair of concrete, and that they represent different approaches and fields.⁷ It was consciously chosen to review literature related to other historic materials as well, as the respective field is more advanced. The review focused on the methods used, their aims and scope, level of detail, and user groups. In the following section, the differences between these guidelines and methodologies will be discussed, and conclusions drawn on the objective of this research.

Guidelines aim at supporting a process, for example from the starting point of an intervention (e.g. damage assessment) through carrying out an intervention. Another characteristic is their often coordinating or educative function. They give support to structure the required steps in the process and remind the user of the required information and/or experts. Differences between the reviewed guidelines can be noticed in the sense that they are either generic - meaning in this case not material specific - or focus on one material only.

An existing guideline specifically aimed at historic concrete is *Historic concrete structures in New Zealand. Overview, maintenance and management* (Reed et al., 2008). The intended target groups are laypersons involved in the decisions making and administration of historic concrete buildings. It outlines the history of concrete in New Zealand, the components and properties of historic concrete, causes of defects and deterioration, and specific problems for historic concrete. Repair materials and techniques are addressed generically to give the reader sufficient background information to understand the different available techniques. Therefore, generalisation and lack of specific references (buildings, publications) is understandable. It gives a first view of the special topics for historic concrete structures and addresses conservation issues; however, explicit handling of the heritage values is missing. Nonetheless, this is until now the first guideline known, which addresses the specific material properties of historic concrete and its conservation and demands to retain heritage values.

A very material specific and clearly defined guideline is the report of the *Fédération Internationale du Béton (fib) Management, maintenance and strengthening of concrete structures* (2002). With the aim to manage and maintain ordinary concrete structures, necessary steps are described, including assessment, remedial actions and reporting. As the target group is rather homogenous (concrete repair experts) and previous knowledge assumed, it is sufficient to mention only the principles of different options (e.g. possible remedial actions).

⁷In Part II and III of the thesis, concrete specific guidelines and recommendations for concrete repair will be addressed in more detail.

A more universal and less material specific guideline is the *Recommendations for the analysis, conservation and structural restoration of architectural heritage* (ICOMOS 2003b), which supplements the *ICOMOS Charter - Principles for the analysis, conservation and structural restoration of architectural heritage* (ICOMOS 2003a). This charter focuses on the structural aspects of monuments, independently of country and material. The primary aims of conservation of structural parts of a monument are addressed, such as safety and the preservation of values, emphasising that different approaches and standards might be necessary for the conservation of historic buildings compared to modern buildings. In this ICOMOS guideline, the suggested steps of the charter “*anamnesis, diagnosis, therapy and controls*” (ICOMOS 2003a, §1.6) are explained in more detail, though the user must refer to other, not mentioned methods, to carry out the work.

In the Netherlands, guidance for building historical surveys and heritage value assessments are given in the *Richtlijnen Bouwhistorisch Onderzoek* (official English translation is *Guidelines for Building Archeological Research*, see *Guidelines for Building*, 2009; *Richtlijnen bouwhistorisch*, 2009). It addresses both administrative and research aspects (research question, aspects to consider during investigation, presentation of findings), and supports the process with checklists. As it is assumed that the user has detailed background knowledge on construction and material history to analyse a building, further background information is not given.

Snethlage’s practical guideline for the conservation of natural stone, *Leitfaden Steinkonservierung* (2005), focuses on the process of data collection and analysis, and the coordination of different experts in the conservation process. It gives sufficient background information to support a conservation process for one specific material. Understanding the dilemmas in practice, such as limited time for research, Snethlage offers guide values for the (technical) compatibility of materials. However, the guideline explicitly leaves the freedom to adapt to the specific requirements of a conservation project, as according to Snethlage conservation cannot be carried out following strict rules and guidelines.

An educative function of a guideline can be combined with dissemination of new knowledge among different user groups, as it can be seen in the *Kalkboek* (Lime book) by van Balen, van Bommel, van Hees, van Hunen, van Rhijn & van Rooden (2003). This guideline focuses on lime-based mortars used in historic buildings in the Netherlands and Belgium, and their use for conservation. As the book has a more educative character and addresses different user groups (e.g. historians, material scientists, heritage care stakeholders), it explains general conservation principles and the fundamentals of material science relevant for lime mortars. As one aim of the book is to disseminate knowledge about historic lime mortars and their conservation, additional background information is given such as the construction history and the methods for the characterisation of lime mortars.

An example for a material-independent guideline can be found in Appelbaum’s *Conservation Treatment Methodology* (2009), which however refers to museum objects and not to buildings. The book is a holistic guideline which addresses all the steps in a conservation process, from the initial request for conservation of the

owner or custodian, the understanding and analysis of the object, the formulation of conservation aims, the principles for the choice of an appropriate conservation technique and the required documentation.

The methods used for the individual steps in the conservation process vary. For data collection and instructions checklists are commonly suggested as done in the *Richtlijnen Bouwhistorisch Onderzoek* (Richtlijnen bouwhistorisch, 2009). For the analysis and identification of correlations of non-numerical data (e.g. historical aspects, heritage values), analytical grids are commonly suggested (Appelbaum, 2009; Lemmens, Nocera & Van Balen, 2006; Zijlstra, 2009).

The level of detail of a guideline depends on three main factors: the homogeneity of the user group, the sophistication of the field, and the function of the guideline. If the user group is expected to be homogenous and to have sufficient background knowledge and experience (fib CEB FIP, 2002; Snethlage, 2005), the description of the individual steps in the process acts more as a reference tool, reminding the user of existing tools and techniques; therefore the guideline can go rather quickly into detail. A common terminology and an understanding of the aims of the field are assumed.

In case of an inhomogeneous user group (for example van Balen et al., 2003), the basic principles and aims of the individual groups have to be explained to the other group, including the used terminology. This is necessary to achieve a good communication between the different groups and to be able to formulate a clear goal of the intervention, which all parties understand. This includes a description of the work of the individual groups and on which principles they are based. In case the guideline aims at helping the coordination of different experts, it is also important for the coordinator to understand the potential of each group.

Besides the homogeneity of the user group, the level of sophistication of the field is of importance. For the repair and maintenance of concrete structures, research, education and experience has reached a high level; this allows a guideline to focus on the main aspects, knowing the user has sufficient knowledge and available references to consult for details (for example fib CEB FIP, 2002). For educative purposes, first the fundamentals of the field have to be transferred to the different (inexperienced) users, and external references are not always available (Appelbaum, 2009; van Balen et al., 2003).

Summarising, the main aim of guidelines is the coordination of a process and explaining the necessary steps in the process. The level of detail varies and depends on the field of application (practice or education), the homogeneity and background knowledge of the user group(s), and if the target field is material specific or generic. In Table 1.1, the aim of this thesis regarding the user group and the sophistication of the field of concrete conservation is outlined based on the insight from the reviewed methodologies and the state of knowledge of concrete conservation.

Table 1.1 Summary of the aims and intended readers/users of the thesis.

Aims	Dissemination and education
	- Awareness of specific properties of historic concrete - References for the characterisation of historic concrete - Insight into the historical context - Overview of existing options for repair, and their suitability for conservation - Reduce interdisciplinary boundaries - Bring together different disciplines - Clarify aims and terminology - Translate conservation principles into material related aspects
User group	Guidance
	- Analysis in terms of relating different aspects of historic concrete - Formulation of conservation aims - Development and evaluation of different conservation strategies
Level of sophistication of user group	Inhomogeneous by profession
	- Restoration architects - Historians - Heritage care institutes - Concrete repair experts - Material scientist
Level of sophistication of the field	Inhomogeneous terminology
	- Homogenous in terms of lacking experience - All groups have little experience with the conservation of historic concrete - The groups have little experience working together ("repair world" and "conservation world")

1.4 Research objective

The aim of this research is to improve the current and future practice of conservation of historic concrete by formulating a dedicated conservation strategy. The research includes a review of the current attitude towards concrete conservation and the uncritical use of common concrete repair practice within the field of concrete conservation. In order to effectively integrate the preservation of heritage values in the conservation process, it is necessary to clarify the relationship between heritage values and material.

The developed approach should enable the discussion of both technical demands and conservation principles, which can be understood by the involved disciplines. In a similar way, guidelines are necessary to evaluate the impact of a proposed conservation strategy on both the heritage values and technical performance. A prerequisite to achieve this aim is to increase the current knowledge of historic concrete; if historic concrete is understood, its properties can be better recognised, leading to a more accurate value assessment. Understanding historic concrete and its specific properties can help understand the present state of conservation. More insight into the properties of historic concrete and common durability problems would help to specify the requirements of a conservation technique.

The main questions addressed in the research are therefore the following:

- *How can historic concrete be preserved together with its ascribed heritage values?*
- *How can a proposed conservation strategy be evaluated for its impact on both the heritage values and the technical performance?*
- *How can we balance the technical demands and the preservation of heritage values, when heritage values and durability issues originate in the same material properties?*

From the main questions, the following secondary research questions arise:

- *What is historic concrete?*
- *What are the possible heritage values of historic concrete and how are they related to the historic concrete as a material?*
- *What are the specific properties and application of historic concrete?*
- *Which properties of historic concrete affect its durability and therefore possibly the heritage values of the material?*

The contribution of this PhD research towards improving concrete conservation will be by providing relevant background information of historic concrete necessary for conservation. A new approach is introduced to integrate the preservation of heritage values ascribed to the historic concrete during conservation, resulting in a dedicated conservation strategy.

1.5 Approach

A deliberate choice was made to focus on the Dutch context. Concrete is often considered as an international material, justifying research independently from a national context. For construction history, however, the national context is relevant, as the dissemination and local application is of interest. The use of local materials and national preferences influence the construction history and the properties of the historic materials. A comparison with other countries can be nevertheless useful to understand the general sophistication of a field. For value assessment, the national context is commonly used as benchmark. In addition, heritage values are influenced by the cultural context.

The Netherlands might not be considered as one of the influential countries when it comes to the history of concrete. Yet, concrete did play an important role in the Netherlands and an understanding of the national context is necessary for the protection of the Dutch built heritage. Therefore, it was intentionally chosen to use Dutch examples to illustrate this thesis: first to confirm the different types of historic concrete used in the Netherlands, second to offer useable reference material for the Dutch context. International references are used for technical aspects, published case studies and for comparison of the state-of-art.

In order to answer the main research questions, the secondary research question “What is historic concrete?” had to be answered first. Little is known about the details of historic concrete and the historical context. Especially reference materials useable during investigations of historic concrete are not available. As a result, historic concrete is often not sufficiently characterised and specific properties, which influence the assessment, both technical and in terms of heritage values, are not identified. Therefore, it was decided to compile a generic reference work for historic concrete in the Netherlands. It was decided to focus on material aspects which influence heritage values, degradation and intervention: the constituents - binders, aggregates, water, and reinforcement - the mix design and the surface finish. An interdisciplinary approach was necessary as each of the three aspects - heritage values, degradation and repair - relate to a different discipline, with the main disciplines material and construction history, conservation techniques and principles, and concrete durability and repair.

The main references for the development of Part I were historic Dutch concrete textbooks and journals, and historic concrete buildings with occasional sampling. Operating in this way, indications can be given on the dissemination of concrete technology and common practices in the Netherlands. As the major Dutch textbooks were published in several editions, changes in concrete technology, its application and appreciation can be reconstructed. The same is applicable for the different editions of official codes, such as the *Gewapend Betonvoorschriften* (G.B.V., Netherlands Code of Practice for Reinforced Concrete) and different editions of Dutch and European standards. As initially most knowledge was imported, main foreign reference works were consulted, as these were referred to in historic doc-

uments. Existing historic concrete buildings (see also Appendix B *Overview of visited objects*) and related publications are used as important references; together they illustrate the history of concrete in the Netherlands and can be used as reference material during investigations of other historic concrete buildings.

Part II starts from the insight gained from the inventory carried out in Part I. The correlation of heritage values, the state of conservation and historic concrete are further analysed, using examples encountered during the inventory phase. Three historic concrete structures, which stood out during the inventory phase, are used as case studies to illustrate the relationship. As cases Fort Bezuiden Spaarndam (1897-1901), the Hofplein railway viaduct (1900-1908), and the earth retaining wall of the unfinished Groot Museum (1921) by H. van de Velde were chosen. Although all three structures are only 20 years apart, significant technological and social changes took place and can be identified. As they are all utilitarian, stronger influences regarding material choice can be expected, and the underlying developments of concrete technology can better be studied. In parallel, the differences in approach between conservation and repair were analysed and repair techniques reviewed from a conservation point of view. This review was based on a literature review, the insight gained from Part I of this thesis and from examples from practice.

In Part III, the cases introduced in Part II are further elaborated. They are used as trial cases for the development of a dedicated conservation strategy, which integrates and balances both preservation of heritage demands and fulfilling of technical demands. Together, the three parts of the thesis represent main steps and knowledge necessary to integrate the preservation of heritage values of historic concrete.

1.6 Thesis outline

The body of the thesis consists of three parts (Figure 1.10), each representing a main step towards the development of a dedicated conservation strategy. After this introductory chapter, Part I provides the background knowledge required for the understanding and characterisation of historic concrete. A generic reference work is given for the following topics, combining both material history and properties:

- Chapter 2 *Historic concrete in the Netherlands*
- Chapter 3 *Binders*
- Chapter 4 *Aggregates*
- Chapter 5 *Concrete mix design*
- Chapter 6 *Reinforcement*
- Chapter 7 *The surface finish of historic concrete*

Related information on the historical context such as guidelines, standards, origin of raw materials and knowledge, are addressed in the respective chapters. Together, these chapters reflect the progress of concrete technology and changing acceptance of concrete from initially a structural material towards an architectural material.

In Part II, the present-day situation of historic concrete will be interpreted and evaluated in order to identify risks for both the historic material and the heritage values, which would require intervention. In Chapter 8, the correlation between historic concrete, heritage values and state of conservation will be analysed. In Chapter 9, the differences between conservation and repair will be discussed and existing concrete repair techniques reviewed for the applicability for the conservation of historic concrete.

In the concluding Part III, the development and evaluation of a dedicated conservation strategy, which includes both technical demands and the preservation of heritage values is shown. In Chapter 10, an approach is suggested which allows the formulation of a case specific conservation aim. This includes guidance of how to translate conceptual aims into material related characteristics. In Chapter 11, the implementation of the conservation aim into a dedicated conservation strategy is discussed, and criteria for the evaluation of different strategies illustrated. In Chapter 12, conclusions are drawn, the initial research questions answered and recommendations given for further research and practice.

In Appendices A to E, supplementary information on obsolete terminology, changes in the Netherlands Code of Practice, used pigments, previous mix designs and an overview of visited objects are given.

The setup of Part I is generic and educative, and can be used as a reference work when investigating historic concrete. As similar reference works apparently do not exist for other countries, Part I can be used as a first orientation for similar countries which, like the Netherlands, depended on the import of both knowledge and (most) raw materials. Considering the complexity of the topic, the underdeveloped state of the field and the scope of the thesis, Part I cannot be comprehensive and must be seen as a starting point for further investigations, both for practice and academic research. Part II and Part III build further on the knowledge gained in Part I, and address an approach to conserve concrete. The introduced approach is illustrated by Dutch case studies. For users inexperienced with one of the disciplines involved - material history, degradation, or conservation - a complete reading is advised to understand the required interdisciplinary approach and the background and terminology of the different disciplines. For experienced users, the individual chapters can be consulted directly, depending on the user's intention.

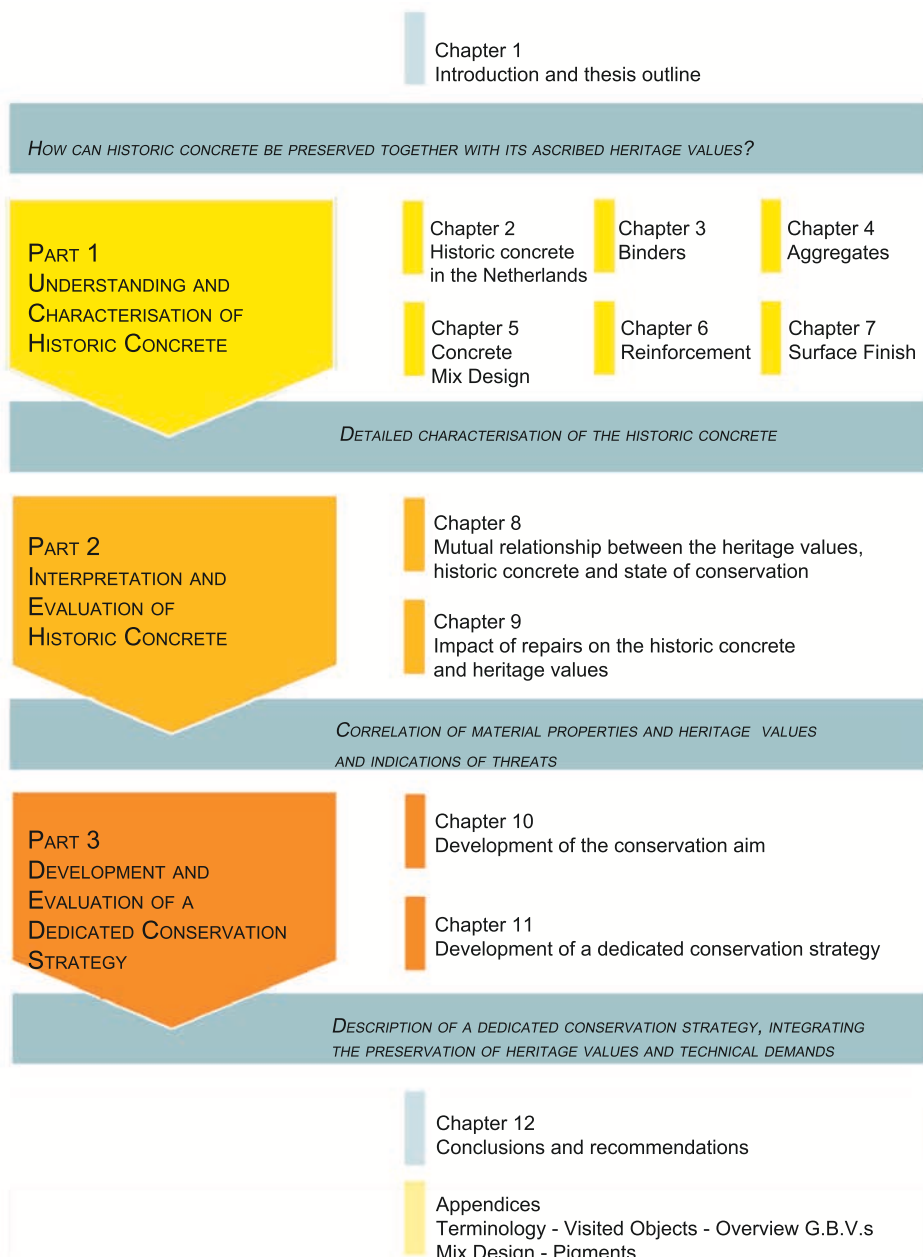
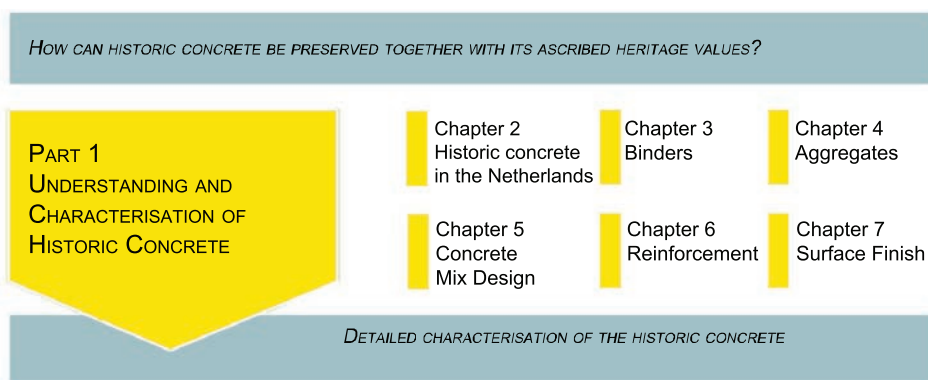


Figure 1.10 Thesis outline.

Part I

Understanding and Characterisation of Historic Concrete



Part outline

The aim of the first part of the thesis is to improve the understanding and characterisation of historic concrete. It focuses on the material history of concrete in the Netherlands.

Detailed background information on the construction history is relevant for many steps in a conservation process, ranging from value assessments, construction historical and technical surveys, and choice of compatible conservation techniques. A detailed characterisation of historic concrete should therefore be the foundation of each conservation campaign. In practice, a main obstacle is a lacking understanding of the properties and historic context of historic concrete.

Therefore, the following Part I offers a generic reference work for historic concrete in the Netherlands. In Chapter 2, a general introduction of the Dutch historical context is given. This chapter concludes with timelines representing the possible material composition and appearance of historic concrete over time. These timelines give guidance during the investigation of a specific historic concrete. In the following Chapters 3-7, different material aspects are discussed in detail, addressing both history and consequences for the durability of the historic concrete. In Part II, the gained insight will be used to discuss in detail the evaluation, interpretation and threats of historic concrete, both in terms of heritage values and technical performance.

Chapter 2

Historic concrete in the Netherlands

Chapter Outline

In this chapter, the Dutch historical context regarding historic concrete will be outlined and the different development and application phases explained. Besides general knowledge and technological progress, the introduction of guidelines and standards, and initial Dutch key players will be addressed. This chapter offers the historical context for the following chapters of the first part of the thesis regarding dissemination of technology and knowledge, and increase of professionalism. The chapter is completed with timelines, indicating specific material properties of a period. These timelines can be used to formulate hypotheses on the material characteristics of a historic concrete, which will be explained in detail in Chapters 3-7.

2.1 Introduction

Understanding the history of a building and the way it was constructed can serve for several purposes. On a general level, historic structures are evidence of previous periods and supplement historic information originating from different sources, such as historic documents or archeological artefacts. Together, they can be used to explain, date and confirm several aspects of former periods varying from the daily life, extension of cities to historic events.

Historic buildings are also evidence of construction history. As a whole, they are the physical evidence of the development of building technology and building material technology. They give evidence of how significant developments in construction and material history changed the way we build and live.

For conservation, existing buildings are not seen as archeological objects but as “living” buildings with a history, which have been in use for maybe centuries and which should stay in use for several more. This requires an investigation of the

historic structures from different points of view. Historic research should identify the historic relevance of both the building and the material; technical research should identify threats affecting both the usability and the heritage values of the monument, and research on a future of the building should integrate both usability and respect towards the heritage values.

The past is investigated in construction historical surveys. It is examined how a building was constructed, including underlying design and material choices, and the influence of the historical context. External influences for example are the availability of raw materials, infrastructure for transport, political circumstances, knowledge dissemination and appreciation of a material. With sufficient background information on a period and construction technique, detailed information can be obtained.

The historic material does not only give information on the period of construction, but can give information on historic events as well. For example, fires can cause colour alterations of stones and concrete, bullet holes can give evidence on the location of gun fights. A recent example is the extensive research carried out on the reconstruction of the murder of the Prince William I, Prince of Orange in the *Prinsenhof* in Delft in 1584, using a bullet hole in the wall as main evidence.

Alterations cannot only be dated by stylistic changes but also by material changes. In particular for artificial and composite materials, the production methods changed during time and thereby materials can have specific characteristics for different periods. Examples for such materials are metals, mortars, bricks and concrete. Whereas for millennia construction and material composition was mainly based on empiric evidence and tradition, a shift towards applying scientifically investigated materials took place in the last two centuries. Parallel, the use of prefabricated building elements and standardisation of materials and design rules increased. The presence of original material can therefore support unambiguous interpretations and reconstruction of historic events.

Regarding historic concrete, its history and variations are often overgeneralised. After the invention of the main constituent, Portland cement, and the filing of the main patents for reinforced concrete, its construction history is often reduced to the structural and architectural achievements enabled by reinforced concrete. This is reflected in construction history practice, where the details of construction and material history are often not identified. A cause is that general background information on the characteristics of concrete in different periods in terms of material properties and design does not exist yet. Too often, generalisations and assumptions are made and national characteristics not recognised. Although concrete is considered an international material and its history shows strong parallels within different countries, unique national aspects exist; these require national orientated research and reference material.

National characteristics can be found in the composition of the concrete and availability of raw materials. In the following chapters, examples of Dutch characteristics will be explained in more detail. In anticipation, a few examples can be already named, such as the Dutch tradition to add trass (a latent hydraulic

additive) to concrete (Section 3.9.1), the higher likeliness of application of Dutch patents such as Muralt's reinforcement system for sea defenses (Section 6.3.3) or Ludwig Adrian Sanders' (1867-1956) patent for metallisation to alter the colour of concrete (Section 7.3.6).

The rate of development of concrete technology is sometimes underestimated. It is often not recognised that within a couple of decades significant changes in material composition and underlying scientific insight took place. Some material characteristics can only be encountered for specific (often short) periods. Understanding the historical context is therefore essential to understand the significance of historic concrete. Factors can be the state of the art of concrete technology, social acceptance of concrete as a building material, production methods, or social-economic circumstances influencing the availability of raw materials and skilled workers. It has to be understood which choices were possible and therefore how far the properties of the encountered historic concrete reflect normal concrete technology, design and application, or innovations. From a technical point of view, detailed material information is necessary as well when evaluating the state of conservation, identifying the cause of damage and choosing possible interventions. Therefore, the success of interventions strongly depends on the quality of pre-investigations as they constitute the reference point for choosing an appropriate conservation strategy (see Parts II and III).

In practice, however, the level of pre-investigation is often insufficient, and the potential of the gained information not fully used. The insight in the material gained in both construction historical and technical surveys is usually not combined, although it could be beneficial for the entire conservation process. During this research, it was observed that construction historical surveys are not always performed; or sometimes, only during or even after a conservation campaign. Additionally, many surveys are not detailed or even incorrect regarding material and construction details. And if carried out, construction historical surveys are usually not available or not consulted during technical surveys. The same applies for the development of conservation strategies, where detailed background information is not available. Furthermore, technical surveys are neither carried out for every conservation campaign. In this context, the need of carrying out and combining historical and technical surveys before the start of conservation works can only be stressed again.¹

Whereas a general challenge is to enhance cooperation between historians and material scientists involved in conservation, a more specific challenge is the current limited knowledge of historic concrete. From the studied cases and literature, a fundamental lack of knowledge of historic concrete appears.

¹First attempts to combine historical and technical surveys have been previously made in the software monitoring tool Monument Damage Diagnostic System (MDDS), developed by TNO and partners in successive EU projects (Van Hees & Lubelli, 2010). MDDS originally focussed on traditional masonry. The development of a concrete damage atlas was initiated during this research.

Common problems encountered in most construction historical surveys of historic concrete buildings are the following:

- Identifying the type of (reinforced) concrete and materials used, and knowledge of construction methods.
- Understanding of the historical context and characteristics of different historical phases.
- Determining significant material aspects which should be preserved.
- Identifying vulnerable material properties related to a historic period.
- Understanding of both obsolete and present concrete terminology.
- Identifying the original appearance and eventual tooling of historic concrete surfaces.
- Distinguishing historic concrete from natural stone and plaster.

Therefore, construction historical surveys and value assessments are often incorrect. As subsequent decisions are influenced by value assessments (e.g. degree of listing, approval of interventions), relevant historic evidence can be endangered or unnecessarily lost.

An underlying cause is the rather limited academic education and research in construction history, and even less in material history. In the Netherlands, mainly art/architectural historians carry out construction historical surveys, which have a limited background in material and engineering history. In addition, the history of 20th century building materials and construction is often not taught and research on this period has only recently started to emerge slowly. Hence, for practitioners few reference works exist, and the complexity of 20th century construction history is not fully understood.

In order to improve the quality of (pre-) investigations of historic concrete structures, a first reference work for the material history of historic concrete in the Netherlands is given in Part I of this thesis. Historical and technical aspects are combined as a detailed understanding of the relation between historic material, possible damage, heritage values and interventions is mandatory for the choice of an appropriate conservation strategy (see Parts II and III).

2.2 Historical context

In the following sections, the different phases of the application of historic concrete in the Netherlands will be outlined. These phases vary in sophistication of concrete technology, preferred constituents, appreciation and application of concrete, each with their own characteristics:

- The transition from plain concrete to reinforced concrete in the second half of the 19th century (Section 2.2.1)

- The exploration and dissemination of reinforced concrete at the beginning of the 20th century (Section 2.2.2)
- Drawbacks leading to standardisation and professionalisation between the two World Wars (Section 2.2.3)
- The combination of confidence in reinforced concrete and the high quantity of re-construction after the Second World War (Section 2.2.4).

Supplementary information regarding the historical context can be found in the Appendices; Appendix B gives a chronological overview of the objects visited during this research, and Appendix C an overview of the different editions of the *Gewapend Betonvoorschriften* (G.B.V., Netherlands Code of Practice for Reinforced Concrete).

2.2.1 19th century: from plain to reinforced concrete

The emerge of concrete structures during the 19th century in the Netherlands has not be fully reconstructed yet. What can be observed internationally is that concrete was applied suddenly for foundations at the beginning of the 19th century; for example the first known English example dates from 1817 (Mordount Crook, 2001). In the second half of the 19th century, plain concrete was applied for military structures in England (Powter, 1978), for the Defense Line of Copenhagen and for the Dutch *Nieuwe Hollandse Waterlinie* (The New Dutch Waterline). At the same time in France, plain concrete structures were carried out inspired by the traditional *pisé* technique, where earth was rammed between a timber formwork. François Coignet (1814-1888) modified the technique, and replaced the rammed earth with a concrete made from hydraulic lime, sand and gravel (Schmidt, 2004).

The use of plain concrete - making up a considerable volume of historic concrete - is often neglected in construction history and overshadowed by the introduction of reinforced concrete. Plain concrete had been used commonly before the development of reinforced concrete in the middle and late 19th century. Plain concrete structures do not only differ in the structural design but also in the used constituents from reinforced concrete.

In the Netherlands, investments in the infrastructure (water canals, railroad) and defense led to the increase use of plain concrete for military and hydraulic structures in the middle of the 19th century, applying it for foundations, hydraulic, and military structures (Heinemann, Çopurğlu & Nijland, 2012). It was commonly made with local materials such as lime, trass and broken bricks; in Dutch this type of concrete was called *brikkenbeton* (see Section 4.3.3). Such concrete was considered to be durable in marine environments and resistant towards shocks, impact and settlement (Dwars, 1923; Hambloch, 1918; Trassforschungsinstitut der Tubag Andernach a. Rh., 1934). These properties also made it suitable for military structures (see Figure 2.1), as traditional brick structures could not withstand the impact of the newly invented explosive shell. Only at the end of the 19th century,

the civil and architectural use of (reinforced) concrete increased and mass produced decorative building elements were introduced.

Plain concrete made with lime and trass was used until the late 19th century for military buildings. In other countries, such as Germany, the use of plain concrete made with lime had already decreased by then (Ast, 1907; Probst, 1935). This was not only due to the decreasing price of Portland cement (see Section 3.6 *Portland cements*), but also due to the poorer properties of lime based binders. Compared to concrete made with Portland cement, it had several disadvantages: besides a lower strength, lime did not harden quickly enough in mass concrete as air (CO_2) could not access the concrete. In fact it could take several decades or even more to harden (Ast, 1907; Storm van 's Gravenzande, 1863). Early 20th century textbooks on reinforced concrete, which are often referred to during historical investigation, seldom address the then outdated plain concrete structures.

The Stelling van Amsterdam (Defense Line of Amsterdam, 1880-1920, Figure 2.2) is a unique example documenting the transition from plain concrete to reinforced concrete (see also Sections 1.3.2 *Review of Dutch concrete conservation practice* and 8.5 *Fort Be Zuiden Spaarndam (1897-1901)*). The role of the Stelling van Amsterdam in the development of concrete technology was one of the criteria to list it as a UNESCO World Heritage Site. Initially, the forts were made from plain concrete. After having sufficient confidence, reinforced concrete was later preferred for fortifications as the dimensions of the elements could be smaller with reinforced concrete, allowing a better disguise of military buildings in the landscape and therefore increase their protection towards hits and visibility. Reinforced concrete could withstand better the impact of shells than plain concrete, and reacted as one monolithic material during an impact (Scharroo, 1909a).

With its large scale projects, own experiments, increasing empirical insight and education of military engineers, the Dutch military had a strong impact on the early concrete technology. Two Dutch military engineers became well known for their influence on Dutch concrete technology, Pieter Wilhelmus Scharroo (1883-1963) and Alphons Constant Charles Godefridus van Hemert (1857-1926). Scharroo became one of the leading Dutch authors on concrete in the first half of the 20th century, contributing to the dissemination of concrete technology, especially with the publications of books and several journal articles. Van Hemert, initially a teacher for statics at the Royal Military Academy in Breda, played an important role in the development of theories, guidelines and the establishment of Dutch concrete companies with his involvement in the Hofplein railway viaduct (1900-1908) in Rotterdam. His company *Hollandsche Maatschappij tot het maken van werken in gewapend beton*, later renamed into *Hollands Beton Groep*, later became a part of the *Royal BAM Group*.



Figure 2.1 Example of the use of plain concrete made with broken bricks in a 19th century military structure. The wall is rendered and with imitated joints (Fortification Hellevoetsluis, built from 1880 onwards; situation 2012, picture Wido Quist).



Figure 2.2 Example of a fort of the Stelling van Amsterdam (Fort Vijfhuizen, 1899, situation 2006).

In the middle of the 19th century, several attempts were made to combine concrete with iron and diverse motives existed.² One early application was for fire proof flooring systems, combining plain concrete vaults with iron beams. Another motive was to create a substitute for wood. The French Joseph-Louis Lambot (1814 - 1887) filed in 1844 a patent, describing the use of a woven mesh and cement in order to produce impermeable objects; the rowing boat he built is frequently mentioned as one of the first reinforced concrete objects (Addis, 2007; Foerster et al., 1912; Ramm, 2007; Scharroo, 1946; Schippers, 1995). The French Joseph Monier (1823 - 1906), who is commonly referred to as one of the key figures in the development of reinforced concrete, filed in 1867 a patent for concrete pots reinforced with a wire mesh.

Monier had several patents, and early applications were for reservoirs which required waterproof structures. The reinforcement mainly functioned to support the form of the object and not yet to carry the tensile strengths (Addis, 2007). This is reflected in the location of the reinforcement, which was not placed in the tensile zone but often in the middle of an object (Foerster et al., 1912). The popularity of Monier's patents for reinforced concrete is mainly influenced by the early patent holders, especially the German Gustav Adolf Wayss (1851-1917) who carried out several experiments to understand the structural behaviour of reinforced concrete in the 1880s and 1890s (Foerster et al., 1912).

The other main historic figure is the French François Hennebique (1842-1921), who introduced the monolithic reinforced concrete structure. Until then, reinforced concrete elements such as floor systems were not structurally combined with other building elements such as brick walls or iron columns. Figure 2.3 illustrates the structural unity of reinforced concrete beams, columns and slabs of Hennebique's patent from 1892. Hennebique's success not only lay in the structural design but also in marketing. Hennebique remained patent holder and only gave license for the construction, meaning that the calculation and design was centralised in a office in Paris (Addis, 2007; Foerster et al., 1912; Ramm, 2007).

Besides the commonly mentioned key figures Monier and Hennebique, several other pioneers were involved in the development of reinforced concrete. One example is the British William Boutland Wilkinson (1819 - 1902), who in 1854 used a reinforcement to carry the tensile strength, in this case iron cables and strips of hoop iron; his design is considered as one of the first using the structural advantages of reinforced concrete (Addis, 2007; Newby, 2001).

By the end of the 19th century several reinforced concrete systems existed, both pre-cast and in-situ. A unified and generally accepted method of how to calculate reinforced concrete did not exist yet, and was difficult due to the variety of reinforcement systems (Addis, 2007).

²A detailed review of the international development of reinforced concrete technology is outside of the scope of this thesis and has been extensively discussed in several publications (for example Addis, 2007; Curbach et al., 2007; Foerster, von Thullie, Kleinogel, Melan, Völker & Richter, 1912; Huberti, 1964; Macdonald, 2003; Newby, 2001; Oosterhoff et al., 1988; Scharroo, 1946; Simonnet, 2005).

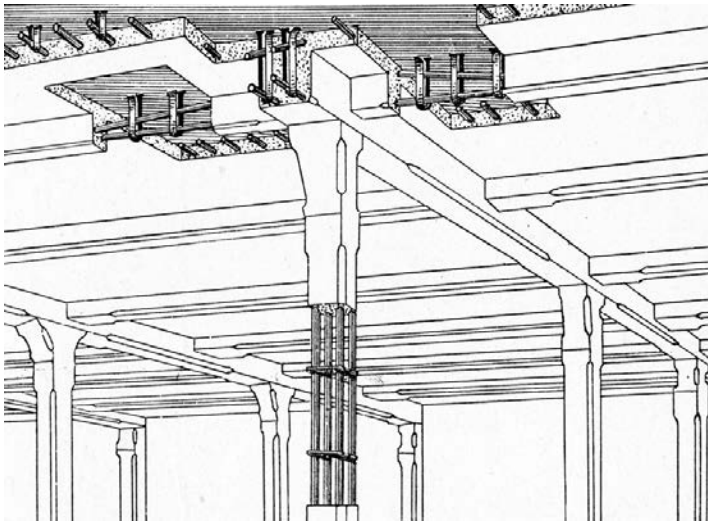


Figure 2.3 Illustration of the Hennebique system, showing the structural monolithic character by combining beams, slabs and columns, and the typical flat strips used as stirrups (Boon, 1931, p. 81).

Besides the general history of reinforced concrete, its application in the Netherlands, including which systems and the moment of introduction, is relevant. A special situation was that the Netherlands had no patent law from 1878 to 1912 (Disco, 1990). However, free application of foreign patents was not easy as the required knowledge was unavailable. In general, the situation was characterised by secrecy on how to calculate reinforced concrete structures (Dicke, 1967).

Reinforced concrete was introduced into the Netherlands by the Belgian company Picha-Stevens, who were holder of the Monier patent for reinforced concrete since 1880. They mainly produced small concrete elements and water reservoirs in the Dutch region of Zeeland. The *Amsterdamsche Fabriek van Cement-IJzerwerken Wittenburg* (later renamed *N.V. Cementijzer Wittenburg*) was formed as a branch in 1890; Ludwig Adrian Sanders (1867-1956) was technical director from 1895-1908 (Disco, 1990; Heerding, 1971; Scharroo, 1946); according to Disco (1990) they had a poor reputation before Sanders joined.

In 1888 the *Rotterdamsche Cementsteenfabriek van Waning & Co.* was founded, and was specialised in prefabricated concrete elements such as sewage pipes and decorative concrete elements (Fens, 1987). Other Dutch companies followed: the *Hollandsche Maatschappij tot het uitvoeren van werken in gewapend beton* in 1902; under the direction of Van Hemert the Hofplein railway viaduct in Rotterdam was one of its first projects (Braak, 1907; Foerster et al., 1912) and in 1901, *F. J. Stulemeijer* in Breda, renamed in 1905 into *Internationale Gewapend-beton N.V.* (Heerding, 1971). Many other companies followed soon and a more detailed overview of companies still existing in the 1930s can be found in Scharroo (1946).

The three assumed principles allowing to reinforce concrete with iron or steel without causing damage to either concrete or reinforcement was: first, that the reinforcement and the concrete perform structurally as one material; second, the coefficient of thermal expansion of concrete and the reinforcement is similar; and third, that the reinforcement would not corrode when it is fully surrounded with concrete (Scharroo, 1909a). Regarding the third assumption, it would take several decades to understand the risks of carbonation induced corrosion (see Chapter 6 *Reinforcement*).

Reinforced concrete did not only replace plain concrete but also steel structures. The advantages ascribed to reinforced concrete compared to other materials were that reinforced concrete buildings were easy to construct with little labour costs, required little or no maintenance, were fire resistant when a sufficient cover concrete was applied and were hygienic (compared to wooden constructions with the risk of fungi); the structure could be designed as a monolithic structure and elements could be dimensioned smaller (Gratama, 1912; Scharroo, 1909a, 1910a).

The impressive properties of reinforced concrete were the new features possible such as large spans, “unbelievable” wide cantilevers, thin columns, seamlessness and its apparently playing with gravity (Gratama, 1912). These technical advantages made reinforced concrete a suitable material for public and industrial buildings (Figures 2.4-2.6), where besides its improved fire resistance its higher structural capacity and wide spans were appreciated. Its sheer endless advantages were supported by the fact that not enough time had elapsed to understand the real durability of concrete, and most disadvantages were ascribed to human limitations such as methods of calculation or quality of execution.

Disadvantages were the difficulties to demolish concrete buildings, excluding its use for temporary constructions, no possibility of re-use of the debris, difficult adaptation of concrete buildings, acoustic problems due to sound transmission, its then disliked grey and dull colour, and that concrete develops its strength only during construction, depending strongly on the raw materials and the quality of execution (Kentie, 1930; Van der Schrier, 1938).

At the turn of the 19th century, despite uncertainties regarding the theories of calculation, reinforced concrete was used in entire Europe, especially in Germany, Austria and France (Bergsma & Homan van der Heide, 1910a; Colby, 1909). However, compared to other countries, the application of reinforced concrete was limited in the Netherlands; Disco (1990) sees the cause in the splitting of the concrete market in two groups: on the one hand professional engineers designing reinforced concrete structures for railway, hydraulic and municipal works and on the other hand small-scale commercial use, which when compared to France and Germany, was far less than what it could have been at that time.

Many “first constructions” have been claimed over time, however, as until now a complete inventory of demolished and still existing Dutch historic concrete structures does not exist, such absolute statements have to be handled with care. The first Dutch reinforced concrete structure, according to Scharroo (1946), was an external wall for the bread and flour factory *Ceres* in Amsterdam dating from



Figure 2.4 Former factory building for Philips Gloeilampenfabriek N. V. (Eindhoven, front part, 1909-1911, A. Beltman, in the back the “Lichttoren” 1920/21, Bureau TABROS; situation 2007).



Figure 2.5 Early example of a reinforced concrete water tower built by *Koninklijke Rotterdamsche Betonijzermaatschappij voorheen van Waning & Co.* (Rijswijk, N. Biezeveld, 1911, situation 2009).



Figure 2.6 Earliest known still remaining factory building in the Netherlands designed according to the Monier system and built by *Amsterdamsche Fabriek van Cement-IJzerwerken Wittenburg* (Calvé factory, Delft, 1905, situation 2010).

1891, however this building has been demolished. The second, a Monier construction, is a culvert from 1892 carried out by *Rijkswaterstaat* (executive arm of the Dutch Ministry of Infrastructure and the Environment) under the supervision of Ir. R.P.J. Tutein Nolthenius (Van der Kloes, 1893).

The now demolished warehouse *Graanpakhuis* in Leeuwarden (1902) was considered the first building with a reinforced concrete frame (Sanders, 1907). A similar but smaller building dating from 1905 still exists in Delft for the Calvé factory (Figure 2.6), and is considered to be the earliest known still remaining reinforced concrete factory building in the Netherlands (see Stenvert & Dekker, 2009). The first reinforced concrete arched bridge was supposed to have been built by *Rijkswaterstaat* in 1900 (Scharroo, 1946). The Cenacle church in Heilig Landstichting (1913-1915, Figure 2.7) was considered to be the first large Dutch concrete dome without ribs with radius of 14,5 m (Scharroo, 1946).³

Another increasing field of application was constituted by prefabricated concrete elements for ceilings and basements; in 1897 more than 100 of such basements were supposed to have been built in Amsterdam only (Scharroo, 1946). Reinforced concrete was preferred for public buildings and for buildings with valuable contents such as museums as it had a better fire resistance compared to traditional building materials (Boon, 1908). The positive experience with reinforced concrete for civil, military and water engineering works led to a quick increase of reinforced concrete works (Scharroo, 1910a, 1946). The confidence towards reinforced concrete increased, influenced by scientific research, which replaced previous empirical evidence (Scharroo, 1909a).

2.2.2 Early 20th century: exploration and dissemination

Despite the previous positive experience regarding the possibilities of reinforced concrete, obstacles still hampered common reinforced concrete practice. Too often, the complexity of concrete was underestimated, calculations not carried out and a presumed easy construction of “just mixing” the constituents tempted to carelessness during the construction works (Scharroo, 1910a). The properties of concrete could vary considerably, as the mix was influenced by the type of construction, changing raw materials, and last not least by the preference of the site manager (Van der Kloes, 1893). Early research questions were related to relevant mechanical properties of reinforced concrete such as elasticity, strength, adhesion of reinforcement and mortar, and to durability aspects like the danger of corrosion and the resistance towards incidents such as fire (Foerster et al., 1912).

As wide experience with reinforced concrete was still missing, reluctance existed to apply reinforced concrete for large civil structures. One example where it was discussed whether it would be sensible to use reinforced concrete is the Hofplein railway viaduct in Rotterdam (1900-1908, Figure 2.8, for details see Section 6.2 *Application and history of reinforced concrete*). Rotterdam was then one

³For comparison, the reinforced concrete dome of a church in St. Blasien, Germany, built in 1910 has a radius of 17 m but still required ribs (Curbach et al., 2007).

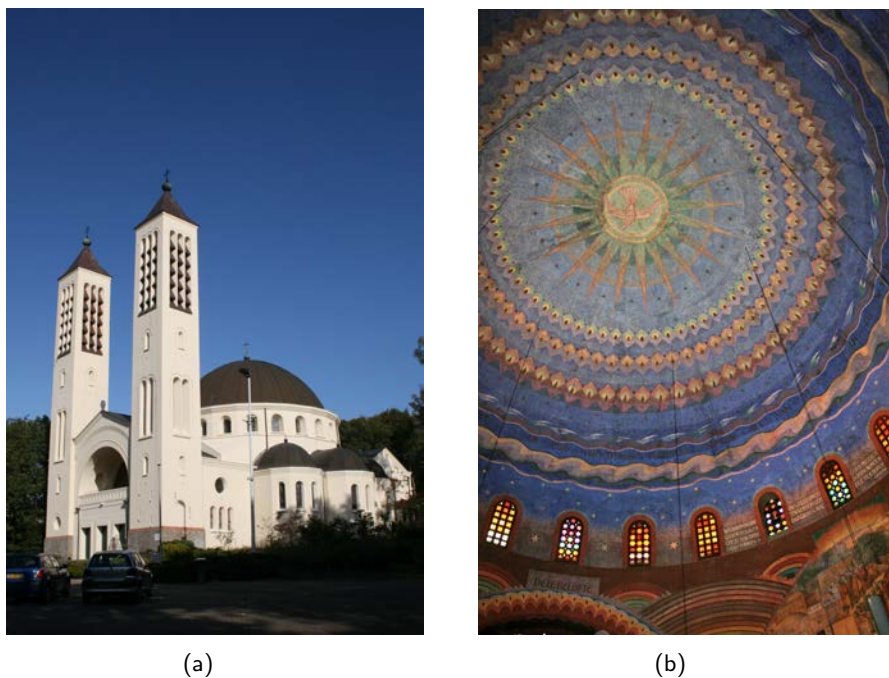


Figure 2.7 Reinforced concrete dome without ribs with a radius of 14,5 m (Cenacle Church, Heilig Land Stichting, J. Stuyt, J. Margry, J. G. Wiebenga, 1913-1915, situation 2011). a) Exterior view of the church with the concrete dome. b) Interior of the dome.



Figure 2.8 The once largest reinforced concrete structure in the Netherlands, the Hofplein railway viaduct in Rotterdam (van Hemert, 1900-1908, situation 2009).

of the early centres of reinforced concrete constructions in the Netherlands, influenced by Wouter Cool (1877-1974), an engineer at the Rotterdam Public Works Department (Disco, 1990).

Besides the city of Rotterdam, *Rijkswaterstaat* was an influential organisation; in 1901 they formed a committee to evaluate the usability of reinforced concrete for their works and visited reinforced concrete structures in England and France (Disco, 1990). Knowledge on how to design and construct reinforced concrete was not easily available at the beginning of the 20th century. The Netherlands were not a centre of research and publication, and depended on foreign sources. Disco (1990) speculates that Dutch engineers (of which most could read French, German and English) would have been informed on research and application of reinforced concrete in other countries, and how the two most important journals (*De Ingenieur* and *Tijdschrift van het Koninklijk Instituut van Ingenieurs*) both reported the latest major foreign publications and works.

As Jacobus Alida van der Kloes (1845-1935) writes in the preface of Th. J. W. van Rossum's book *Gewapend Beton vrij gevolgd naar P. Christophe* (Reinforced concrete based on P. Christophe, van Rossum, 1902) the demand for knowledge dissemination could not be answered solely by publications in journals anymore and an own Dutch textbook was necessary. The urgent questions of engineers and practitioners in the field were the calculation of reinforced concrete construction and its construction itself. Van Rossum (1902) freely adapted Paul Christophe's French *Le béton armé et ses applications* (Christophe, 1902) to the Dutch situation. It was the first Dutch book addressing reinforced concrete in terms of theory, design, material, and execution. Kersten's German textbook *Der Eisenbetonbau* (Kersten, 1907a) was translated and adapted in two volumes by Bergsma and Homan van der Heide (1910a; 1910b). As Dutch experience was limited, the described practice often referred to situations abroad. For the underlying theories, state-of-the-art and outstanding examples, reference was often made to leading foreign publications (for example Ast, 1907; Büsing & Schumann, 1905; Christophe, 1902; Foerster, von, Wienecke, Völker, Spitzer & Melan, 1908; Foerster et al., 1912; Memmler, Burchartz, Albrecht, Janesch, Rappold & Nowak, 1907; Spitzer, Nowak, Gehler, Colberg, Elskes, Labes, Bastian, von Shitkewitsch & Stettner, 1908; Taylor & Thompson, 1905; Von Mecenseffy, 1911).

The increased application of reinforced concrete and accidents caused by laymen (e.g. collapse after a too early removal of formwork), required an education of engineers, architects, supervisors and workers, which led to an increase of Dutch publications and handbooks for self-study, often written by practitioners (for example Boon, 1908, 1914, sa; Muller, sa; Scharroo, 1910a,b, sa; Verhey, 1912, 1915). Publications based on Dutch research appeared as well. Van der Kloes, a trained architect and later professor for building materials at the *Technische Hogeschool Delft* (now Delft University of Technology), published about the properties of concrete, the different constituents and reinforcements based on his experiments and case studies (Van der Kloes, 1893, 1908a,b,c). Sanders was one of the few Dutch researchers who gained international reputation (Bouvy, 1967; Sanders, 1907; Von

Emperger, 1904). Although Sanders was not academically trained, he learned the profession in practice at the *Amsterdamsche Fabriek van Cement-IJzerwerken Wittenburg*, and carried out research on the mechanical properties of concrete and on different existing theories of calculation.

In early textbooks, bias cannot be excluded in the selection of projects as works by competing Dutch companies are not mentioned. Sanders, for example, was in competition with Van Hemert and Hennebique and professional enough to mention Van Hemert's theory in his review of existing theories (Sanders, 1907), but did not mention their works and only used examples of his company *Amsterdamsche Fabriek van Cement-IJzerwerken Wittenburg*.

With increasing demand for knowledge, reinforced concrete became part of the civil engineering curriculum at the Technische Hogeschool Delft in 1905 as part of lectures on building materials by Prof. van der Kloes and part of a course on roads and bridges by Prof. Everts (Disco, 1990). In 1907, a special reinforced concrete course was given by Everts, with S. J. Rutgers as guest lecturer. In his inaugural speech, Rutgers (1909) addressed the then current challenges of concrete and concrete research: difficulties to calculate statically indeterminate structures, leading to only approximate results, and lacking reference values for the elasticity theory for different concrete mixtures, causing inaccuracy. A part-time chair for reinforced concrete technology was founded in 1918 with Jan Adrianus Bakker (1883-1965) as professor, and only in 1953 a full-time chair was appointed to Prof. Arend Martin Haas (1899 - 1983) (Disco, 1990).

A practical requirement was the development of guidelines to control calculations and construction of reinforced concrete structures. Besides the military, *Rijkswaterstaat* and public work departments in larger cities such as Rotterdam became more and more interested in reinforced concrete, initiating the development of the *Gewapend Betonvoorschriften* (G.B.V., Netherlands Code of Practice for Reinforced Concrete) (Deuten, 2003). A committee was installed in 1906 and a draft code published under the name *Voorschriften voor beton-ijzer* in 1909 (Koninklijk Instituut van Ingenieurs, 1909). The idea of developing guidelines was not new and already existed in other European countries. Drafts existed in Switzerland in 1903, in France in 1906, in 1907 Austria and England and in Denmark in 1908 (Scharroo, 1910a, 1946). In the Netherlands special attention was paid to the Prussian code from 1907 and its draft from 1904 (Scharroo, 1910a).

In 1912, the first G.B.V. was published. From the beginning materials, execution and calculation were addressed.⁴ The publication of the G.B.V. 1912 supported the growth of the reinforced concrete market, as it made calculation and design methods widely accessible. To keep the G.B.V. up to date with concrete technology, both practice and science, a permanent commission was formed in 1914 (Dicke, 1967).

⁴See Appendix C for an overview of the content and changes of the different editions of the G.B.V.

2.2.3 Interwar period: standardisation and professionalisation

Besides the import of knowledge, the Netherlands initially also depended on the import of raw materials, especially Portland cement (see Chapter 3 *Binders*). This dependency on other countries influenced the material choice, as due to wars and the economic situation in other countries, the availability and prices could be affected negatively. The properties of the concrete could be influenced as well, as for example the cements originating from different countries could vary in quality and performance. Fraud was not uncommon as material standardisation did not exist yet in the Netherlands. The G.B.V. 1918 did give a definition of Portland cement, but ignorance amongst users and a guiding dictum was missing, which facilitated the use of binders of a lower quality (Scharroo, 1927a,d). One reaction was the introduction of standards from the end of the 1920s onwards; the other the starting up of own cement factories (first ENCI, later CEMIJ) to overcome the dependence on foreign countries, which had proven vulnerable during and after the First World War (details see Chapter 3).

The exploration and understanding of the behaviour of concrete consequently increased. First, durability issues such as of concrete exposed to sea water led internationally to research on different binders, resulting in the acceptance of blast furnace slag cement (see Section 3.8.3). In the Netherlands, *Rijkswaterstaat* was a supporter of the exploration and introduction of new technology. Under the supervision of the engineer Johannes Aleidis Ringers (1855-1965), several experiments were carried out to identify suitable cements for the construction of the *Noordersluis* (Northern sluice) in IJmuiden (Ringers, 1924; Visser, 1927a,b).

In general, the use of reinforced concrete increased in the 1920s. By the 1930s, reinforced concrete had become a common construction material. The high prices of bricks and the lack of housing in the early 1920s stimulated the experimental use of concrete. Several housing projects were constructed in concrete, with *Betondorp* in Amsterdam (literally Concrete Village, Figure 2.9) as the most well-known (Kuipers, 1987). Other (international) developments were the architectural exploration of new features (e.g. wider spans, cantilevers, higher structures for example Figure 2.10). Until then, the leading role was left to civil engineers, who already knew how to take advantage of the new material. However, an architectural concrete language was still missing. Concrete buildings imitated the look of buildings constructed in traditional materials (Gratama, 1912). Nevertheless, architectural developments supported by new construction methods did appear soon; buildings of the Modern Movement are now commonly associated with early concrete architecture and reference is often made to the leading architectural role of the Netherlands (Kentie, 1930; Prudon, 2008; Vischer & Hilberseimer, 1928).

Dutch examples for the architectural use of reinforced concrete are mainly characterised by the application of existing possibilities to implement new visions of housing and working, such as access to daylight and fresh air. The Van Nelle Factory (1925-1931, Figure 1.2) by Johannes Andreas Brinkman (1902-1949) and



Figure 2.9 Housing made with one of the many building systems used in Betondorp, the Bron system; a three leaf prefabricated reinforced concrete wall made with different concrete types: the outer leaf with gravel as aggregate, the interior and insulating layer with breeze (*sintels*) and in between a breeze filling. The concrete surface was originally brushed but is now plastered (see Kuipers, 1987, p. 191) (Amsterdam, D. Greiner, 1923-1925. Situation 2008).



Figure 2.10 The first high-rise housing project in the Netherlands, the “Wolkenkrabber”, was made with a reinforced concrete structure (Amsterdam, J. F. Staal, 1932, situation 2009).

Leendert Cornelis van der Vlugt (1894-1936) and the open-air school (Figure 2.11a) by Jan Duiker (1890-1935) are well-known examples of this period. These new architectural styles took mainly advantage of structural possibilities and discussed less the aesthetical treatment of the concrete surface; many façades were rendered. Less known is the exploration of different techniques and materials to alter the appearance of concrete, including the increased use of prefabricated decorative elements (Figure 2.11b).

Major changes in material production and standardisation occurred in this period. With the increased use and acceptance of reinforced concrete, opportunists appeared. Scharroo (1925) commented that although concrete was widely used, not everybody was familiar with the basics of concrete. Its presumed easy construction led to an increase of construction companies during the First World War; common causes for poorly executed works were the lack of calculations, the use of poor quality materials, especially cement, and not enough skilled supervisors, altogether causing a decline of the reinforced concrete economy (Scharroo, 1925). Scharroo even described the situation as an anarchy, jeopardizing serious construction companies and achievements of concrete technology. Recommended were regular controls of construction works and concrete mixes to ensure the required quality (Scharroo, 1946). As reaction, a union of reinforced concrete contractors was formed in 1928, the *Beton-Aannemers-Bond*, which aimed to promote the development of concrete construction, provide loyal competition amongst members, give support for drawings and calculations, and to increase knowledge dissemination. For prefabricated concrete, a similar union, *Bond van Fabrikanten van Betonwaren in Nederland*, had already been formed in 1922 with the same aims (Scharroo, 1946).

Internationally, research on concrete technology increased and new construction methods allowed the implementation of scientific theories such as on mix design. An emerging research topic was concrete durability and new findings were applied such as a rudimentary consideration of exposure classes (for details see Section 6.5 *Concrete cover of the reinforcement*).

The first generation of concrete textbooks was replaced with new editions, updated with new projects, guidelines and standards, and extended with newest insights into concrete technology (Bergsma, 1934; Boon, 1920, 1931; Scharroo, 1916, 1921); concrete durability was explicitly addressed, including reinforcement corrosion caused by cracked concrete or stray currents, fire resistance and chemical influences (see for example Bergsma, 1934). In his fourth edition, Boon (1931) included an increasingly important scientific aspect: concrete mixes. Van der Kloes' books on building materials were now written with the help of a new generation of authors (Van der Kloes, Jacobs, Tjaden & Wentholt, 1924, 1925).

A new author in the field was W. van der Schrier (1901-1967), a civil engineer teaching concrete and mechanics at a technical college in Amsterdam (*Middelbare Technische School voor Bouwkunde*). Van der Schrier's first textbook was published in 1938 (Van der Schrier, 1938), based on the lecture notes used at college. Therefore, mainly the application and to a lesser extent the scientific

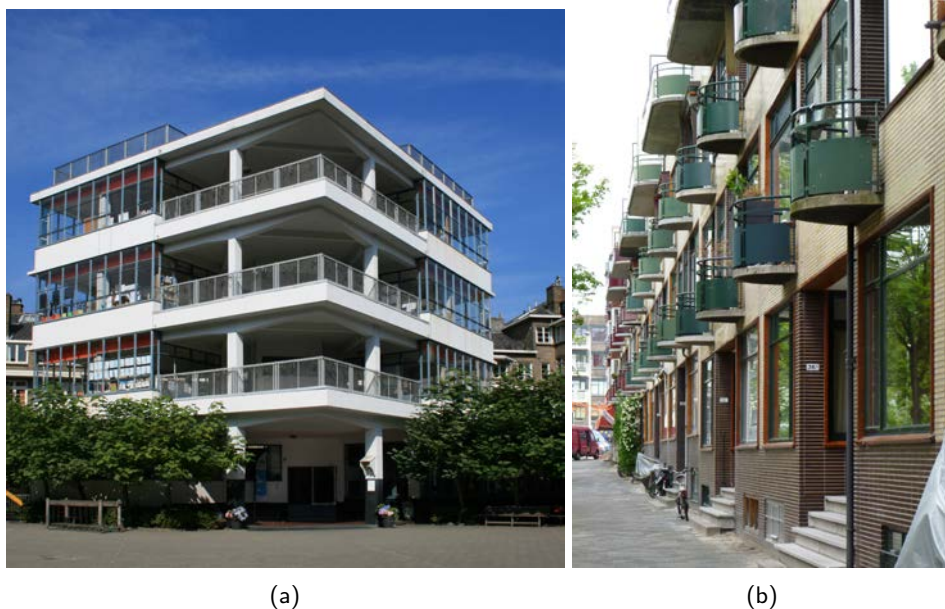


Figure 2.11 Two examples of architectural use of concrete in the 1930s. a) White rendered concrete building (school *Eerste Openluchtschool*, Amsterdam, J. Duiker, 1929-1932, situation 2007). b) Use of coloured concrete for balcony slabs and for stairs (Housing Rotterdam, Schepenstraat, 1937, W. Th. ten Bosch, situation 2010).



Figure 2.12 Bunker, part of the Atlantic Wall (Hoek van Holland, 1942, situation 2011).

background of reinforced concrete were addressed. The second edition (Van der Schrier, 1942), which was postponed until the G.B.V. 1940 was published, showed several changes regarding the symbols and nomenclature of reinforced concrete, maximum allowed stresses, and introduced building site supervision (*bouwcontrole*). In general, Dutch textbooks were still holistic, explaining constituents, construction methods and calculation of reinforced concrete buildings. In building and construction textbooks, the design, detailing and construction of reinforced concrete buildings were addressed more commonly than previously (for example Wattjes, 1922, 1930, 1936). Specialised journals followed the (international) progress of reinforced concrete technology, for example the journal *Het Bouwbedrijf* (from 1924-1938, published by the *Betonbond*) edited amongst others the previously mentioned authors Wattjes, Scharroo and Tjaden.

In the G.B.V., the developments are reflected as well. In the 1930 edition, different types of binders were allowed for the first time (see Chapter 3), the terminology changed from *ijzer* (iron) to *staal* (steel), reflecting the metallurgical developments of the last years and terminological changes within the metal industry (see Chapter 5); more detailed rules for the mix design were prescribed (see Chapter 4) and exposure classes had to be considered. In the 1940 edition, the supervision of construction works is addressed and the allowed stresses for the reinforcement increased due to the new development of steel types (Dicke, 1967).

2.2.4 Second World War and reconstruction: confidence and quantity

With the Second World War and the occupation of the Netherlands by Germany, less civil reinforced concrete buildings were constructed. Raw materials were limited, especially timber, and building materials had to be asked for centrally in Berlin already in 1940. By then, import of cement from Belgium and Germany had decreased, as both countries needed the cement themselves. In July 1942, a ceasing of constructions was announced for the Netherlands in connection with the declaration of the “*Totalen Krieg*”. Materials and people were used to build reinforced concrete bunkers and other military buildings for defence lines such as the Atlantikwall (Figure 2.12, see also Bosma & Wagenaar, 1995; Pollmann, 2006).

After the Second World War, much of the Dutch infrastructure and housing had to be rebuilt. The reconstruction was coordinated by Ringers, the same engineer carrying out experiments on binders for the Noordersluis in the 1920s (see Section 2.2.3). In the Netherlands and in other countries, the demand for fast reconstruction resulted in the promotion of the use of prefabricated concrete. Reinforced concrete was often used as it was the easiest material to obtain (Schelling, 1950b). However, bricks became available again at the end of the 1940s and formed a competition for industrialised mass housing (Bosma & Wagenaar, 1995).

The Dutch government subsidised prefabricated building systems. The advantage of using these systems was less use of raw materials (wood and nails for formwork). It allowed easier, less labour intensive and fast construction, which

was important as skilled workers were lacking. Prefabrication was more economic as construction was independent of weather and elements could be reproduced. Minor disadvantages were that the structural advantages of monolithic concrete constructions could not be used and that there was a dependence on a minimum infrastructure for production and transport (Kleinlogel, 1949).

The demand for fast reconstruction gave impulse to new construction methods such as the use of ready-mixed concrete. In 1947, the first Dutch ready-mixed concrete plant opened to support the reconstruction of Rotterdam: *N.V. Betonmortelfabriek Rotterdam "Befaro"*. The advantages were faster placing of concrete, a more constant quality, and simplification of the construction process. In 1957, only 9 ready-mixed concrete plants existed, in 1960 already 73 existed and in 1970 a total of 177 were in operation (Heerding, 1971).

Besides for mass housing, reinforced concrete was commonly used for public buildings. This increased application was based on the on-going evolution of concrete technology. The architectural use of concrete went on improving, especially for methods of surface finishes (Scharroo, 1951).

Knowledge on reinforced concrete was now easily available, supported by the new, still existing, Dutch journal *Cement*, which was founded in 1949. The first generation of authors of concrete textbooks was slowly replaced by new authors. Widely known were the textbooks by the already mentioned W. van der Schrier (1948; 1949; 1951; 1953; 1960; 1968). Even humoristic publications on concrete technology appeared (Anon., 1968). Besides the academic training of civil engineers and architects, the professional education of concrete labourers increased such as specialists for placing formwork, reinforcement and pouring concrete (Grin & van der Veen, 1950; Scharroo, 1940, 1942a, 1950a; Van der Schrier, 1957).

The review and development of the G.B.V. could not be managed internally anymore and external experts were consulted from T.N.O. (*Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek*, Netherlands Organisation for Applied Scientific Research), and the Technische Hogeschool Delft (Dicke, 1967). Novelties in the G.B.V. 1950 were the calculations for mushroom floor constructions; in the G.B.V. 1962, supervision and improvements on calculation were emphasised, and concrete quality classes introduced.⁵

Internationally, it was perceived that the main aspects of reinforced concrete were understood, both design and durability, allowing an optimisation of material use and element size. However, degradation mechanisms which can require decades to show symptoms were not known or fully understood yet (e.g. carbonation induced corrosion, alkali-silica reaction, chloride induced corrosion).

⁵The quality of the concrete was defined in the G.B.V. 1962, article 12, in three classes: K160 with a minimum cube strength after 28 days of 1,6 kN/cm², K 225 with a minimum cube strength of 2,25 kN/cm² and K300 with a minimum cube strength of 3,0 kN/cm².

2.3 Historical context and material properties

Properties and composition of historic concrete are influenced by the circumstances of its construction period. When investigating historic concrete, a first hypothesis on possible material characteristics based on the historical context can therefore be made. Circumstantial information may be helpful, such as:

- Framework indicating allowed/common practice (guidelines and standards)
- State-of-the-art of concrete technology indicating what was common, advanced, rare, or experimental
- Special circumstances causing deviations (e.g. wars, reconstruction periods)
- Key dates causing changes in material use and design
- Origin of constituents and influences on availability and quality
- Influence of client, architect, engineer, typology and location
- Changes in terminology

With such background information, further technical and historical research can be specified. As not all aspects can be identified directly on-site, some answers can only be found by further material investigation. This can include non-destructive techniques (e.g. cover meter to indicate non-visible reinforcement in an early concrete structure) or minor destructive techniques (e.g. small sampling to identify type of pigments and likeliness of colour alterations, or a rare binder). Historic concrete structures can be evaluated in their historical context as normal, low or high quality, common or unusual, or innovative for the period.

Common prejudices encountered in practice that historic concrete is always of poor quality may not be generalised. However, specific characteristics making the concrete more vulnerable can be identified for different periods, reflecting inexperience, inaccuracy and even overconfidence. Earlier structures may have been more vulnerable to immediate degradation due to poor execution (e.g. voids, displaced reinforcement); yet, if well constructed, they can be durable.

The properties of historic concrete dating from the first decades of the 20th century may, to a certain degree, be unpredictable and rarities are not excluded. For example, new binders were explored, standards lacking and fraud not uncommon, demanding for an open eye and mind for surprises during investigations. Trial and errors related to this innovative period may have consequences for both quality and historic significance of the historic concrete. Damage due to deleterious properties of some aggregates and admixtures have only appeared after decades, and insight has only increased in the last decades of the 20th century. Structures from the Post-War years were generally produced under a higher quality control and thereby reducing the appearance of early damage symptoms. As these structures were optimised in design and material use, they have fewer reserves and can show relatively more damages when aged; a too little cover of the reinforcement in

combination with a reduced cement content is hereby mentioned in practice as a common problem causing corrosion. In the following chapters, durability issues in combination with specific constituents or designs will be discussed more in detail.

To guide case specific investigations, an overview of the application of different materials used for historic concrete is presented in Figures 2.13 to 2.17. The shown timelines reflect the likeliness of certain constituents and the historical possibilities; the possibility of exceptions has to be considered, for example in experimental applications or for aesthetical reasons. As no complete inventory of the material history of historic concrete exists yet in the Netherlands, the presented period of application is indicative; a slightly earlier or later application is not excluded.

For all periods, the role of the planners, owners, and construction companies has to be kept in mind. Their experience and tendency for conservative or innovative approaches played a major role in material choices and achieved quality. It has also to be remembered that concrete technology and appreciation of concrete underwent fast changes within a few decades. Some techniques or constituents were only used for a limited period and their use is now often forgotten and therefore not considered during investigations. Detailed information for the respective constituents or techniques can be consulted in the Chapters 3-7.

2.4 Conclusions

Although the Netherlands are often associated with bricks (see for example the manifest by the 1941 exhibition *Nederland bouwt in baksteen*, The Netherlands build in brick), concrete did play a major role during the 19th and 20th century. Internationally, Dutch works might have been overshadowed by larger and more innovative structures abroad; nevertheless, the Netherlands were an active participant in concrete technology from the beginning. Dutch characteristics of historic concrete can be encountered as well, varying from the development of own techniques to preferences for specific constituents and merging raw materials and knowledge from different countries.

Regarding the material history of concrete, the changes related to different periods can be identified in the historic concrete. From the historical context, preliminary indications can be given on the to be expected characteristics of the historic concrete, which will be discussed in detail in the following chapters.

As the Netherlands was not a cradle of concrete technology, initially knowledge and raw materials had to be imported. As until now most research of the construction history has focused on leading countries such as Germany, France or the United Kingdom, it would be interesting to compare the dissemination of knowledge and technology with other countries with a similar historical context as the Netherlands. By this, national characteristics can be identified better, and evaluated whether the innovations of the leading countries were internationally applied and whether current perceptions on the history of concrete are too strongly influenced by British, German or French works.

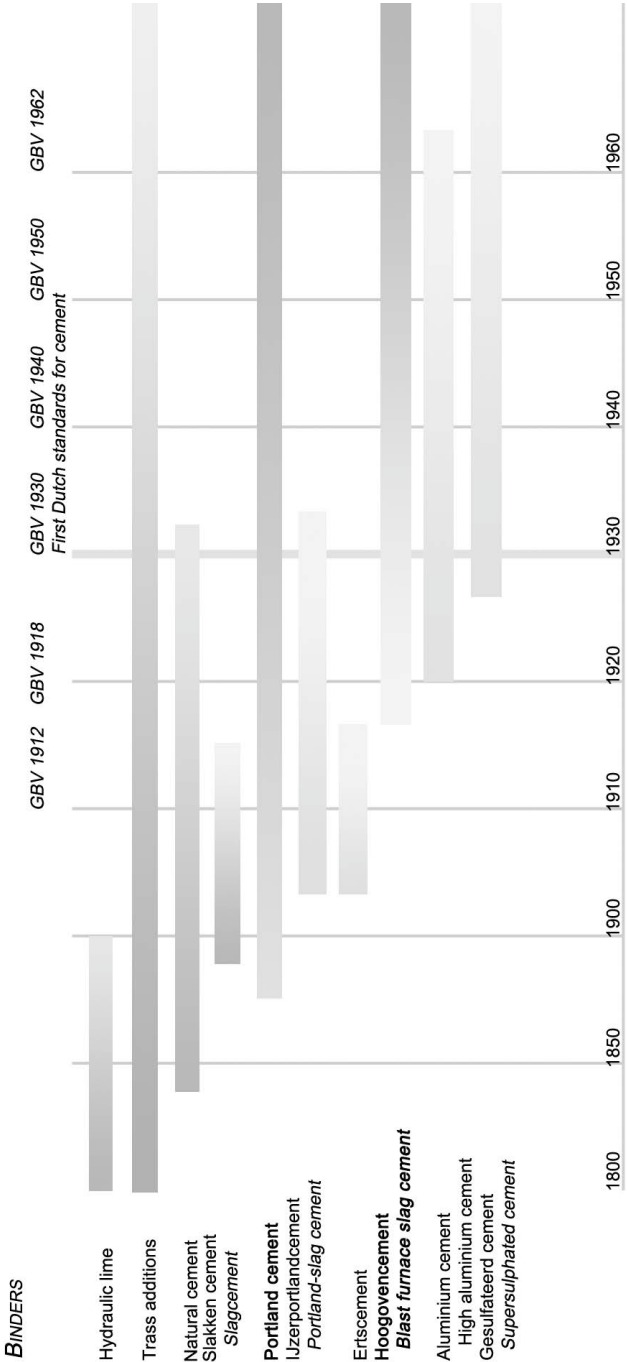


Figure 2.13 Timeline for binders used for historic concrete. For details see Chapter 3.

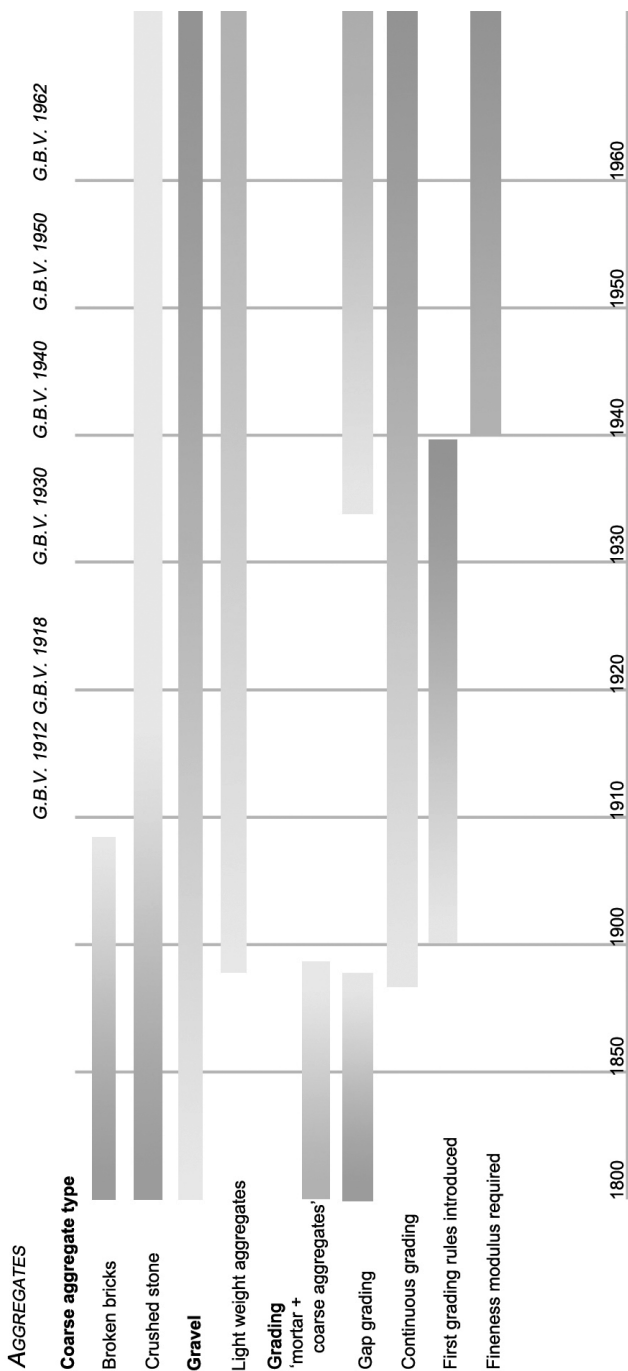


Figure 2.14 Timeline for aggregates used for historic concrete. Only the main tendencies are shown; for aesthetical purposes or special structures the use of different aggregates types and grading is possible. For details see Chapter 4.

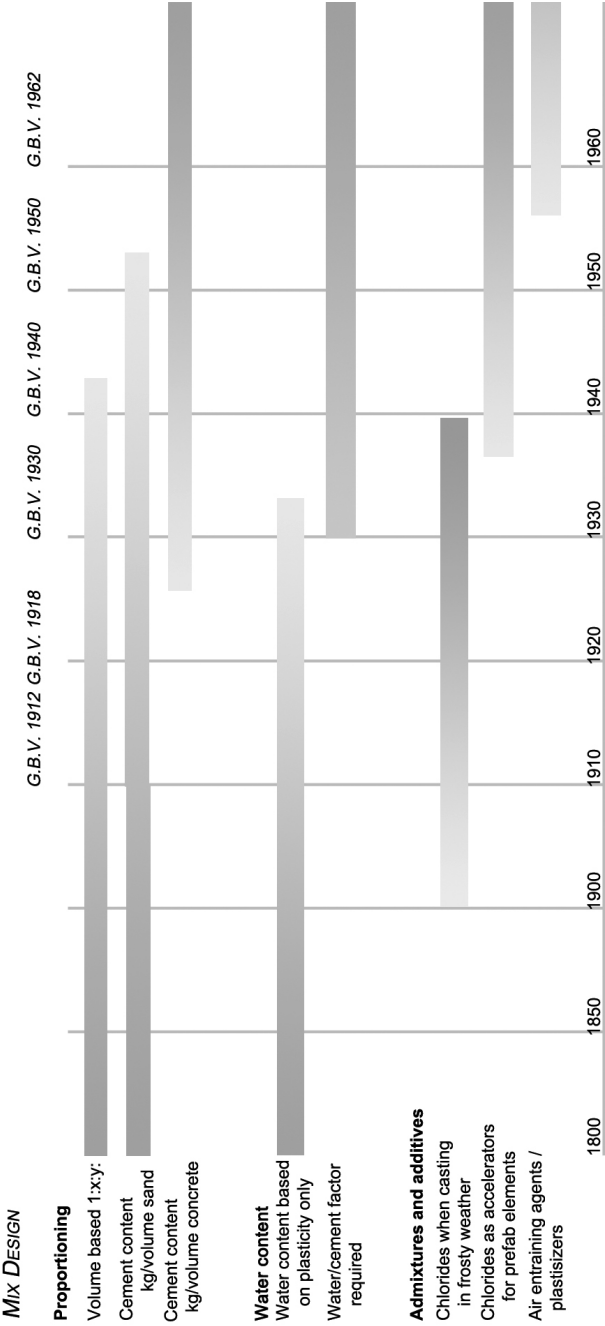


Figure 2.15 Timeline for the mix design for historic concrete. For details see Chapter 5.

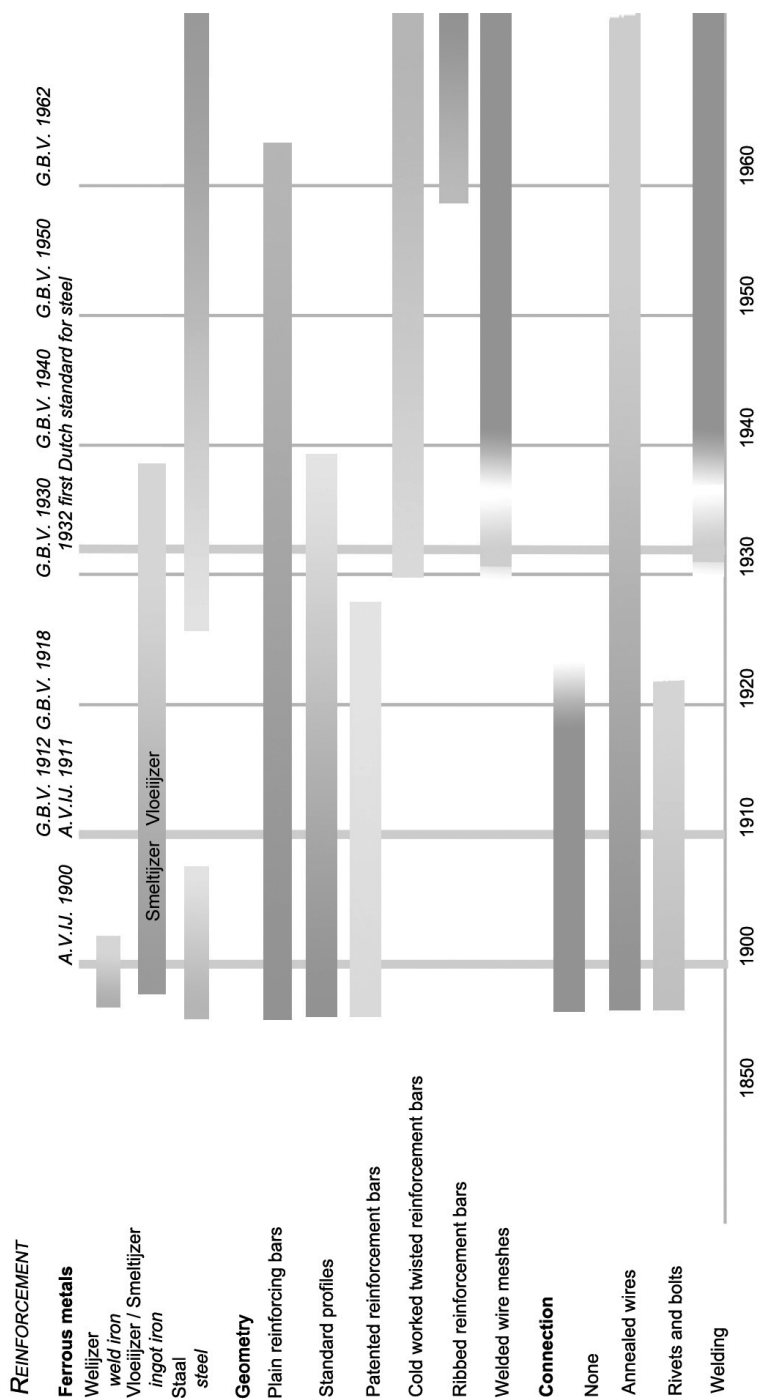


Figure 2.16 Timeline for the reinforcement used for historic concrete. For details see Chapter 6.

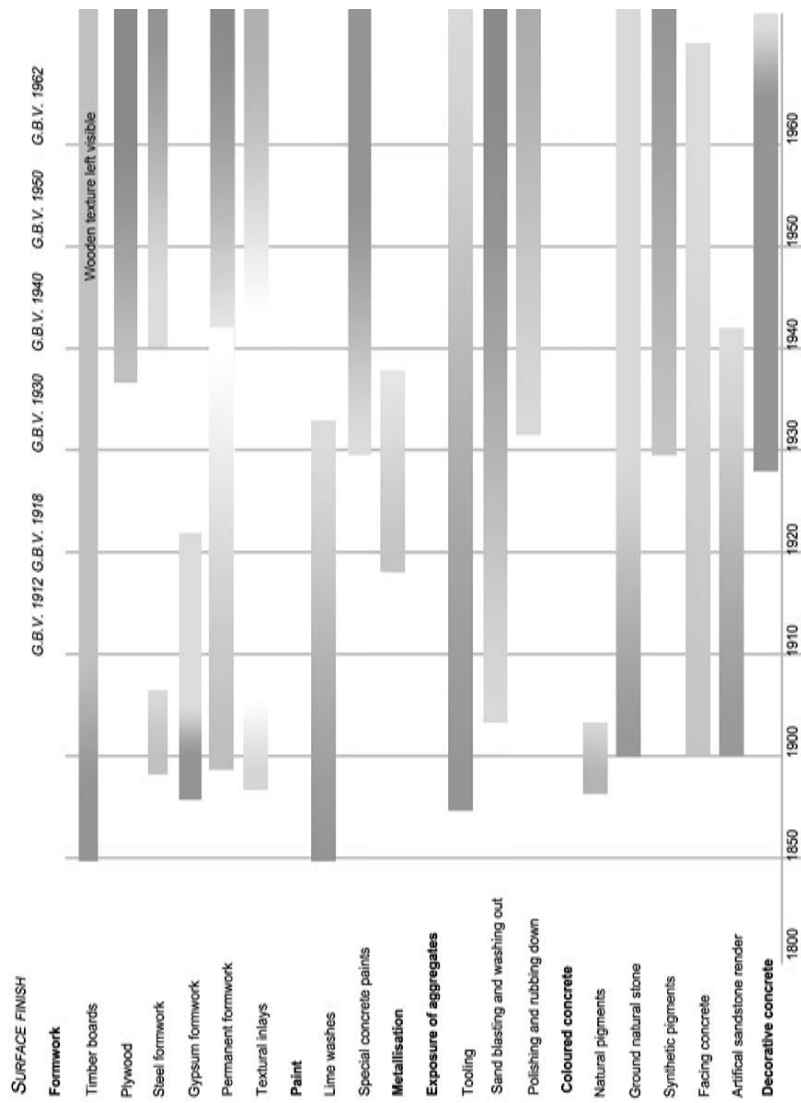


Figure 2.17 Timeline for surface finishes applied to historic concrete. Cladding and render in general are not considered. For details see Chapter 7.

Chapter 3

Binders

Chapter outline

Chapter 3 is the first chapter addressing the constituents used for historic concrete. Here, the history of the binders used for historic concrete in the Netherlands will be outlined. After a general overview of their development, their application and production in the Netherlands will be discussed. The increase of the quality will be illustrated by changing quality aspects, influenced by the insight from durability issues on the composition and the introduction of standards. In detail the main cement types, Portland cements and slag bearing cements will be discussed, as well as some less known cement types which have been used for historic concrete. By outlining the historical context, information is available on their application, changing composition and relevance for the Netherlands. This allows preliminary indications on binders encountered in historic concrete based on the construction period, typology and environment.

3.1 Introduction

Binders, especially cements, are a key component for concrete as they bind the aggregates. As mentioned in Section 1.2, the definition of cements was, historically, broader, including hydraulic limes. Binders allowed the fabrication of artificial stone which can be cast into any shape. Binders not only influence the strength of the concrete but also its durability, as not all perform equally in all environments. Several binder types were used for historic concrete; yet, in practice the view is often narrowed to Portland cement and blast furnace slag cement.

Concerning the use of binders for historic concrete in the Netherlands, a few publications exist which explicitly address cement but, they have a stronger focus on the economic history of the cement factories and key figures (Felder, 2006;

Heerding, 1971). In international literature, the situation is comparable and publications focus mainly on economic history, key moments or structural aspects (see for example Curbach et al., 2007; Huberti, 1964; Hurst, 2001; Macdonald, 2003; Sutherland et al., 2001). In technical books on the chemistry of cements or the durability of concrete, historical changes in the composition of cement are occasionally discussed (Bogue, 1947; Stark & Wicht, 2001).

For conservation and the related investigation of a specific historic concrete more detailed information on the possible applied cement type and its properties is necessary. This includes information on the historical context in terms of the introduction and legal situation of different binders, the changing perception on their advantages and disadvantages, and indications for their use. Additionally, information is required to understand obsolete cement terminology for the correct interpretation of historic documents.

A correct identification of the binder is not only historically interesting but technically relevant for conservation. It can give insight into the durability and possible causes of damage, and an understanding of its properties is essential for the choice of a compatible repair technique.

A current obstacle is the little and limited reference data available to support the identification of historic cements, especially as some cements were only used for a limited period, or properties have changed during time. A detailed chemical analysis of historic cements is outside the scope of this chapter; instead, it is a starting point to identify possible binders and to broaden our current knowledge on cements previously used. More recent developments from the late 1960s onwards are also not discussed, as they are outside of the investigated period.

3.2 Development of binders used for historic concrete

The binders used for historic concrete are mainly synthetic hydraulic binders and their development dates back to the 19th century with the increase interest in the manufacture of hydraulic binders. A hydraulic binder reacts chemically with water, which means that the binder can harden underwater and does not dissolve in the presence of water. These properties made it an attractive building material for hydraulic structures.

Early cements were either made from naturally hydraulic materials or the raw materials were calcinated. For comparison, modern cements are made by a careful selection and proportioning of the raw materials and sintering the raw materials at temperatures above 1450°C. Natural hydraulic binders (e.g. hydraulic lime and lime-pozzolana) have been used for construction since prehistoric times, with a major advance in Roman times (see Section 1.2).

The use of mortars declined in the Low Lands after the fall of the Roman Empire but increased again with the upcoming of natural stone buildings at the turn of the first millennium, later including the use for brick work. A Dutch, and internationally distributed, latent hydraulic binder was *trass*, also known as *Dutch tarras*, which was manufactured since the 17th century and used for marine structures. Trass is a natural pozzolana made by grounding tuff stone, which was imported from the German Eifel region (see Section 3.9). As a toll had to be paid on trass but not on tuff stone, the tuff was ground in the Netherlands, with Dordrecht as one of the main centres; the trass produced there was known as *Dordtsch cement*. In the second half of the 19th century, these tolls were abolished, leading to the import of German trass (Herfeldt, 1884; Scharroo, 1946; Storm van 's Gravenzande, 1850). More details on the history of trass production and use in the Netherlands can be found in Herfeldt (1884), brochures by the German company Tubag (Trassforschungsinstitut der Tubag Andernach a. Rh., 1934), Scharroo (1946), Heerding (1971) and van Balen et al. (2003).

In the 18th century, attempts were made to develop substitutes for trass using local raw materials. Examples are *Amsterdamsch cement*, developed in 1783 by A. Booij, who used silt from the river IJ, and in 1792 the *Utrechtsche* or *Cazius cement* by the Utrecht company *Wed. Cazius & Zonen*, made from clay from the Utrecht region. Due to their red colour, a generic term for these binders was *rood cement* (red cement). To distinguish them from natural cements (trass, pozzolana), they were called *kunstcement* (artificial cement) (Scharroo, 1946; Storm van 's Gravenzande, 1850, 1863; Van der Kloes et al., 1924; van Dijk & Van der Baan, 1952).

These cements were commonly used for mortars and less for concrete. In the Netherlands, the general use of artificial cements for governmental buildings was forbidden in the middle of the 19th due to bad experience, probably caused by poor production methods; instead, the use of trass was advised (Storm van 's Gravenzande, 1850, 1863). The use of local clay from the sea as a raw material for the production of artificial pozzolana with a good quality was noticed abroad; however, fraud was known that this type of cement was sold to England as trass, which was considered superior (Pasley, 1838; Storm van 's Gravenzande, 1863).

A characteristic of these binders is that their manufacture was empirically based. In the 18th century, there was a general increase of research amongst engineers (Addis, 2007). The properties of hydraulic binders were investigated to overcome the dependency on Dutch tarras or Italian pozzolana. The usability of Vitruvius works, previously the main reference for hydraulic binders, for other regions with deviating raw materials than mentioned in the works, was questioned. This led to research such as by the French L. J. Vicat (1786-1861) on the manufacture of hydraulic lime using local raw materials (Vicat, 1837). Vicat's work is characterised by a chemical background to understand how to modify the composition of argillaceous rocks with limestone, and how to control the production of hydraulic lime, which was then also called natural cement (Bogue, 1947).

Other research aims were to understand what makes binders hydraulic. In 1756, the British J. Smeaton (1724-1792) studied the hydraulic properties of different binders such as lime, trass and addition of lime; his works are considered as the turning point from the traditional use of hydraulic limes to a scientific approach. Smeaton was inspired by a research trip to the Netherlands to study the use of trass for marine structures, resulting in the use of hydraulic mortar for the construction of the Eddystone lighthouse (1756-1759) in England; this project is often considered as the starting point of the use and research of modern hydraulic binders (see for example Addis, 2007; Bogue, 1947; Huberti, 1964; Hurst, 2001; Pasley, 1838; van Balen et al., 2003).

Shortly after Smeaton's findings, the English James Parker obtained a patent for a manufactured natural hydraulic binder in 1796, which he called *Roman cement* referring to the hydraulic binder of the Romans (see Section 3.7). Roman cement was not sintered and no clinkers were formed.

In the transition phase from traditional hydraulic limes to the newly developed hydraulic binders, a change in terminology can be observed. In the 19th century the term cement could refer to any type of hydraulic binder, such as hydraulic limes, pozzolana, ground brick, or natural or Portland cement (Bogue, 1947; Michaëlis, 1867; Van der Kloes, 1893). Characteristic for a cement was that the main constituent was silicon dioxide (SiO_2) and the raw materials were exposed to high temperatures (Storm van 's Gravenzande, 1850, 1863). To distinguish between artificial cements and hydraulic lime, the latter was also referred to as water cement, where water was used as a synonym for hydraulic (Pasley, 1838). In France, artificial pozzolana were known as *ciment* and Vicat suggested to replace the term with hydraulic lime (Pasley, 1838).

The next milestone in the development of synthetic hydraulic binders is seen in Joseph Aspdin's (1778-1855) invention and patent of *Portland cement* in 1824, which he named as such since the colour of the cement is similar to the colour of Portland limestone (see Section 3.6). Portland cement was produced at higher temperatures, leading to the formation of clinkers. A reliable production of a good quality Portland cement was only possible from about 1845 with the ability to control high temperatures required in the kiln (Hurst, 2001).

The use of Portland cement was not restricted to concrete, in fact it was initially often used as a bedding mortar or to cast decorative elements; other uses were for engineering works and less for architectural purposes (Pasley, 1838; Reid, 1869). The quality of the Portland cement improved in the late 19th century by the increasing scientific research on the composition, especially by the Germans John, Delbrück, Bleibtreu and Michaëlis (Bergsma, 1934; Van der Schrier, 1951). Despite intensive research, the details of cement chemistry and the composition of Portland cement were still unknown in the 1920s (Burchartz, Jordan, Schluckebier & Rappold, 1927).

At the end of the 19th century the use of concrete had increased and the use of other raw materials with hydraulic properties, such as slags, investigated. With the increasing experience and insight into the durability of Portland cement,

alternatives were researched, especially for marine environments where Portland cement was not very durable. At the turn of the 19th century the German W. Michaëlis (1840-1911) patented a sulphate-resistant Portland cement with a low aluminium oxide content, the so-called *Erzzement* (iron-ore cement; Van der Kloes, 1908c, see Section 3.10.1). Another option for marine environments was the use of slag-bearing cements (see Section 3.8), which faced initially a strong prejudice as their raw materials were waste products of the iron production. After initial doubts, slag bearing cements became accepted due to their superior durability in marine environments in the Interwar period and common after the Second World War. Investigation in cements suitable for aggressive environments, the increase of construction speed, and substitutes for Portland cement led to the development of new cement types during the 20th century (see Sections 3.8 to 3.10).

3.3 Historic binders used in the Netherlands

Before discussing the binders used for historic concrete in the Netherlands it is necessary to clarify the terminology of historic cements as a direct translation into present day English concrete terminology is not always possible. Historic cements cannot be compared to present day cements solely on their historic terminology, as not all cement types are identical to modern cements, neither in terms of composition nor in naming. Another challenge is the different connotations between Dutch and English. For example, the historic Dutch *hoogovencement* is technically comparable to the English blast furnace slag cement but does not reflect the differing production methods, as for *hoogovencement* the blast furnace slag and Portland cement clinker were interground whereas for the English and American blast furnace slag cement, the Portland cement and blast furnace slags were usually mixed in the cement factory. To avoid a change in the definition of the different cement types and risking the loss of national characteristics, the Dutch terminology will be used in this thesis when an exact translation is not possible without loss of information.

In practice, mistakes occur even when using only Dutch terminology, as background knowledge is missing to enable historians the differentiation between the different historic cements types. Too easily cements are wrongly categorised, for instance, different slag containing cements (*IJzerportland cement*, *slakkencement*, or *hoogovencement*) are categorised as *hoogovencement*, neglecting the differences in material composition and terminology. For example, in the historic review of cements in the Netherlands, Bot (2009) only mentions *hoogovencement*; from the context, dates and references mentioned, it is obvious that *IJzerportland cement* (Portland-slag cement) is meant sometimes.

The differences in terminology and material composition have already been a challenge when unifying the standards for cement in the European Union. While cements had the same or similar names, their properties could differ depending on the production country. In an enquiry of the European Committee for Stand-

ardization carried out in the 1970s, nearly twenty different types of cements were identified; a second enquiry from 1990 showed fifty cement types (NEN-EN 197-1:2000). With regard to the increasing free trade in the European Union in the second half of the 20th century, a unification of the standards and cement types in the member states of the European Union was aimed at. In an attempt to achieve a conformity between the member states, a classification of common cements was defined in the European standard NEN-EN 197-1:2000. Cements conform to NEN-EN 197-1:2000 are labeled CEM, and are categorised in five main groups CEM I-V. The CEM classification has become the common terminology amongst practitioners and academics. A direct placing of the historically used cement types is not possible, yet for orientation of the different used cement types an overview is given in Table 3.1.

In the Netherlands, the use of reinforced concrete emerged in the last decades of the 19th century, a time in which Portland cement was the most commonly cement used for concrete structures (see Figure 2.13 *Timeline for binders used for historic concrete*). An often neglected aspect within construction history of concrete is the use of plain concrete in the 19th century made with hydraulic lime and trass.

The use of trass for (plain) concrete structures can be explained by the Dutch tradition of producing trass and its application for marine structures. Besides application for bridge foundations, early examples for the use of trass cement and lime-trass cement can be found in some forts of the Stelling van Amsterdam (Defence line of Amsterdam) dating from the late 1880s, such as the fort near Abcoude (1884-1887), the fort in the Pampus (1887-1895) and the fort near IJmuiden (1881-1888) (Gaasbeek, 2003).

Other examples are the foundations of the sluices of the Zuidwillemsvaart canal (1824-1825), using a mix of 20 parts Belgian lime from Visé and 15 parts of trass from Cologne; the foundations of the St. Andries sluice and the steam pumping station Bommerlerwaard (1854-1855) using a mix of 6 parts of Belgian hydraulic lime from Chaudfontaine and 7 parts trass (Storm van 's Gravenzande, 1863). Concrete made with lime was named *kalkbeton* (lime concrete) and its use is known from 19th century military building. In the fort near Vijfhuizen (1897-1899) the use of *kalkbeton* is mentioned besides a concrete with Portland cement (see Figure 3.1). The use of lime declined as it did not offer sufficient corrosion protection for the reinforcement.

Before it was used for concrete in the Netherlands, Portland cement had been used for mortars for brickwork or floor constructions, in, for example, a prison in Amsterdam from 1850 (Storm van 's Gravenzande, 1850, 1863). It soon became the preferred cement type for reinforced concrete. Most early textbooks reflect the preference for Portland cement, as it was the main cement mentioned for reinforced concrete structures (Boon, 1908; Minister van Oorlog, 1906; Scharroo, 1910a; van Rossum, 1902). An exception are the textbooks by Van der Kloes, who as professor for material science, carried out research on different binders (Van der Kloes, 1893, 1908c; Van der Kloes et al., 1924). According to Van der Kloes (1893, 1908c), two

Table 3.1 Comparison of proportions of blended cements.

	Scharroo (1916)				Boon (1920)				Van der Kloes (1924)				Scharroo (1946)				Van der Schrier (1938; 1942; 1951)				NEN-EN 197-1:2011			
	PC	S	L		PC	S	T		PC	S			PC	S			PC	S			PC	S	T	
Portland cement	100	0	0		100	0	0		100	0			100	0			100	0			100	0	0	
IJzerportland cement (Portland slag cement)	70	30			≥70	≤30			≥70	≤30			≥70	≤30			≥70	≤30			80-94	6-20		
Hoogoven cement (blast furnace slag cement)					10-30	70-90			15-30	70-85			15-69	31-85			34-65	35-66			20-34	66-80		
Trass portland cement (Pozzolanic cement)					50-70		50-30														65-79	21-35		
Slakken cement (slag lime cement)																					5-19	81-95		
																					65-88	11-35		
																					45-64	36-55		

Legend: PC-Portland cement; S-blast furnace slag ; T-trass; L-slaked lime.

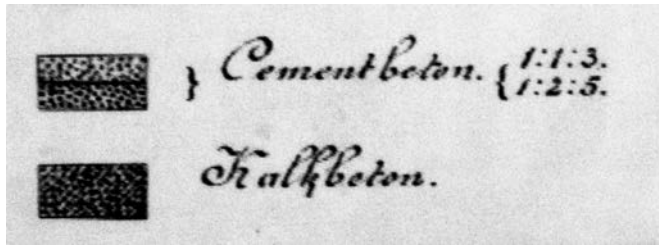


Figure 3.1 Legend from a historic construction drawing (Fort Vijfhuizen, 1897) showing the use of *cementbeton*, meaning concrete made with *Portland cement*, and of *kalkbeton*, a concrete made with lime.



Figure 3.2 Dutch advertisement for Belgian Portland cement with an emphasis on artificial Portland cement (*kunstmatig Portland cement*) (Van der Vooren, 1931).



Figure 3.3 1930s advertisement showing a variety of available cements (Van der Vooren, 1931).

binders were advisable for concrete: Portland cement and trass-lime. Portland cement was advised when a high early strength was required and its higher price less relevant; otherwise, trass-lime should be used.

The preference for using Portland cement is reflected in the early concrete terminology. Generally, the Dutch *beton* or *cementbeton* (concrete or “cement concrete”) referred to a concrete with Portland cement, whereas when other binders were used it was distinguishable in the naming such as *cementtrassbeton* (cement-trass-concrete) or *trassbeton* (trass-lime concrete) (Boon, 1920; Verhey, 1912).

In the first decades of the 20th century, caution was required when using Portland cement, as sometimes natural cement (see Section 3.7), which had similar properties, was sold under the name Portland cement (Boon, 1908; Scharroo, 1927a). Natural cement is produced with clays which have by nature the required properties for cement and are not further proportioned or sintered, causing fluctuations in quality. Therefore, the term artificial cement (*kunstcement*, see Figure 3.2) was emphasised, meaning synthetic Portland cement such as it can be read in the *Gewapend Betonvoorschriften* (G.B.V., Netherlands Code of Practice for Reinforced Concrete). Natural cement was produced in Belgium and exported

to the Netherlands (Boon, 1913, 1920, 1931; Van der Kloes, 1908c; Van der Kloes et al., 1924). Besides natural Portland cement, *slakkencement*, a mixture of trass and slag (see Section 3.8.1), was considered a natural cement and often prohibited (for example Minister van Oorlog, 1906). In the G.B.V. from 1912 and 1918 only artificial Portland cement was allowed. In practice, *ijzerportlandcement* (Portland slag cement) was not strictly forbidden contrary to the use of later introduced *hoogovencement* (blast furnace slag cement) which remained forbidden (Boon, 1920).

The following Table 3.2 gives an overview of the changes in the different editions of the G.B.V. regarding the allowed cement types. The changes reflect the technical progress and the changing perception of different cements. The G.B.V. were mainly intended for standard reinforced concrete structures and did not want to hinder the development of concrete technology. Therefore a deviation of the standards was possible for special structures designed by competent engineers (Van der Vooren, 1931). The changes are based on gained empirical and scientific insight, therefore the use of other cement types earlier than recommended in the G.B.V. cannot be excluded under specific circumstances.

In the 1920s, a wider discussion on possible cement types was carried out, and a differentiation of the use of cements based on an exposure class, mainly marine or normal, is noticeable. The quality of cement improved due to the increased scientific research on material properties and on production. It was possible to produce reliably higher quality cements and new cement types appeared (for example high-aluminium cement), opening new possibilities for the use of cement and concrete (Scharroo, 1927f). A major development was the acceptance of *hoogovencement* (blast furnace slag cement). From German companies it was known that a reliable quality was achievable and in 1917 *Hochofenzement* (German term for blast furnace slag cement) was considered equal to Portland cement in Germany. The Dutch were more conservative and its use forbidden. This reserve was due to the strong market position of Portland cement and previous bad experience with poor blast furnace slag cements encountered in practice (Heerding, 1971). A change of minds occurred as the quality had improved and insight had been gained into its superior suitability for marine environments.

The first large scale application of *hoogovencement* (blast furnace slag cement) in the Netherlands was for the construction of the locks, the Noordersluis (Figure 3.4), in the harbour of IJmuiden (1919-1930). *Rijkswaterstaat*, who was the owner of the lock, supported the use of this new cement type. Together with its main engineer Ringers, the use of blast furnace slag cement was studied during this project (Nijland & Heinemann, 2008; Ringers, 1924; Visser, 1927a,b). Despite the positive experience and the intention to set up a Dutch *hoogovencement* factory, it was still strongly discussed if the use of *hoogovencement* should be permitted in the next edition of the G.B.V. (Heerding, 1971). The use of blends of Portland cement and blast furnace slags was allowed with restrictions in the G.B.V. 1930 (Van der Vooren, 1931).

Table 3.2 Overview of the cement types allowed in the different editions of the G.B.V.

	G.B.V. 1912	G.B.V. 1918	G.B.V. 1930	G.B.V. 1940	G.B.V. 1950	G.B.V. 1962
Portland cement	✓	✓	✓	✓	✓	✓
<i>IJzerportland cement</i> (Portland-slag cement)	-	-	(✓)	(✓)	(✓)	✓
<i>Hoogovencement</i> (Blast furnace slag cement)	-	-	(✓)	(✓)	(✓)	✓
<i>Aluminium cement</i> (High-aluminium cement)			(✓)	(✓)	(✓)	(✓)
<i>Trass-Portland cement</i> (Trass-cement)	-	-	-	-	-	(✓)
<i>Gesulfateerd cement</i> (Supersulphated cement)			-	-	-	(✓)
<i>Slakkencement</i> (Slag-lime cement)	⊖	-	-	-	-	-

Legend: ✓ Allowed; (✓) Restricted use allowed; ⊖ Not allowed; - Not mentioned; Not yet available.



Figure 3.4 The Noorderlsuis in IJmuiden; experiments were carried out to identify a suitable binder for the brackish water (Rijkswaterstaat with J. A. Ringers, lock houses by J. Emmen, 1921-1929, situation 2012).

In the 1930s, a variety of cement types could be encountered. Portland cement was still the most commonly used cement, also due to the fact that the production and quality of *ijzerportlandcement* (Portland-slag cement) and *hoogovencement* (blast furnace slag cement) was not always reliable. Officially, *ijzerportlandcement*, *hoogovencement* and *aluminiumcement* (high-aluminium cement or ciment fondu) were allowed with restrictions in the G.B.V. (Van der Vooren, 1931); *erts cement* (iron-ore cement, see Figure 3.3) was available but not mentioned. If used, these cements were applied for special constructions or aggressive environments (Boon, 1931).

After the Second World War, the lack of materials, not only raw materials but also coal for the production of cement, led shortly to consideration of other, inferior, cement types such as natural cements in case of emergencies (van Dijk & Van der Baan, 1952) or the use of new types of artificial pozzolana such as fly ash (Leeuw, 1955, Section 2.10.2). Despite such initiatives, Portland cement and *hoogovencement* became the most used cement type in the Dutch post-war reconstruction period; under special circumstances also high-aluminium cement was used. Slag-lime cement and trass-Portland cement, which were occasionally used before, did not play a role anymore (van Dijk & Van der Baan, 1952). In the G.B.V. 1962, Portland cement, *ijzerportlandcement* and *hoogovencement* were finally considered as equal, and only high-aluminium cement, trass-Portland cement and supersulphated cement required special permission prior to use.

3.4 Origin of cements used in the Netherlands

Whereas the Netherlands were known for its trass production and export, its own Portland cement industry appeared relatively late. In his detailed review of the history of Dutch cement production, Heerding (1971) discusses the reluctance to introduce Portland cement into the Dutch market. At the end of the 19th century, Dutch trass producers protested against the use of the new, more expensive and imported Portland cement. Portland cement was then mainly imported from Germany and Belgium, and in smaller quantities from Britain and France. Portland cement was first produced in Britain; German production started in 1855 in Stettin under the direction of Bleibtreu; the named *Stern cement* was considered of high quality (Huberti, 1964; Reid, 1869). Doubts existed over the quality of non-British cements; yet, due to the quality obtained by the German's scientific approach (constrating the mainly empiric British approach), the use of German cements increased (Foerster et al., 1912). In Belgium, cement production started in 1872 with the cement factory *Dufosse et Henry* and a wide cement industry was situated in the Meuse basin (van Dijk & Van der Baan, 1952).

A successful Dutch production of Portland cement was difficult as the raw materials (lime, clay, and coal necessary for the kiln) were not available in geographical nearness. Scharroo (1946) saw the high transport prices for lime, which was scarce in the Netherlands, as the main reason for failure of the first Dutch companies. Another obstacle was the limited knowledge on cement production. In 1870, Portland cement was first produced in the Netherlands by E.H. Roggenkamp in Delfzijl, where he erected a small-scale factory (Heerding, 1971). Initially, the approach of the factory was experimental as Roggenkamp tried to understand the production of Portland cement. He used a local clay, Achterwijn-slik, and English lime; the quality of his cement was tested by foreign experts, which stated a good quality for a beginner. This cement was mainly applied near Groningen, in the northeast of the Netherlands. Due to a lack of financial profits, the factory was closed down after 10 years. Another Portland cement factory was erected in Delfzijl in 1874: *Sybrand Hoven's stoomcementfabriek* (steam cement factory), renamed into *Reese & Co.* in 1883, and lasted until the 1890s. *Brantjes & Lankelma* (1882), situated in Purmerend, produced Portland cement using clay from the North Sea (Heerding, 1971). Under German influence, a first Portland cement factory opened in 1875 in Vijlen, Limburg: the *Aachen-Vijlener Portland Cement Werk*. The factory initially produced natural cement and only later Portland cement and closed down in the early 1920s (Felder, 2006). In Vijlen, chalk stone and Maastricht limestone were easily available, making it a strategic point for cement production; there, a second factory opened in 1894, the N.V. Nederlandsche Portland-Cementfabriek, which also did not operate for long (Heerding, 1971).

Without succeeding in producing an own Portland cement, the Dutch stayed dependent on imported cement. To regulate the Dutch market, the main importing German and Belgian companies formed the *Nederlandsche Cement Syndicaat*



Figure 3.5 Advertisement of the Dutch Cement syndicate, indicating a Dutch preference for German Portland cement (Scharroo, 1923).



Figure 3.6 Advertisement for four Dutch cements (Van der Vooren, 1931).

(Dutch Cement Syndicate, Figure 3.5) in 1904. In 1906 English and Norwegian companies joined. A problem was the varying quality of the foreign cements. Rutgers (1911) described his impression after a visitation of different factories in Germany, Britain and Belgium: fluctuations in quality were caused by using different raw materials, production methods and degree of quality control, which was better if the cement came from a large factory. Fraud was known, especially in Belgium, where barite, lime or sand were secretly added or natural cement sold as Portland cement. Rutgers concluded that no good quality could be encountered in the factories visited in the region of Tournai. Original packaging of the cement was not a guarantee for good cement, as fraud was committed in the factory itself. Therefore, chemical analyses of cements were recommended.

With the beginning of the First World War in 1914, the Nederlandsche Cement Syndicaat only represented the interests of German companies, as Belgium could not export anymore. After the war, Belgium became the main cement exporter to the Netherlands, as its reconstructed cement industry was at the highest technical levels and production had increased (Heerding, 1971). With the lack of cement and the increase of the prices during and after the First World War, the need for an own

Dutch cement industry grew. Additionally, the quality of the available cements decreased as in the 1920s, the Dutch market suffered from a lack of standards for cement and the testing of the quality of the cement was difficult. Even cements from Switzerland, Austria and Poland were imported for a short period in the 1920s as the transport costs in Germany dropped due to the inflation (Anon., 1932a). The strong competition amongst the importing companies led to fraud, and cheaper natural cement was sold as Portland cement (Scharroo, 1946).

Dutch initiatives on having an own cement production started more structurally during and after the First World War. Van der Kloes attempted a revival of the Dutch *rode cement* (red cement) using silt from the river IJ and shell-lime but was not successful (Van der Kloes et al., 1924; van Dijk & Van der Baan, 1952). The possibility for a Dutch Portland cement factory was explored by the military engineer and concrete expert Scharroo and the architect Mart J. Stam (1886-1957) in 1916. A location near Utrecht behind the *Nieuwe Hollandse Waterlinie* (New Dutch Waterline) was strategically chosen, balancing the transportation of raw materials from Limburg and possibility for military defence. Due to a lack of financial resources, the project was not carried out. In 1917, a small factory was founded near St. Pietersberg in the province of Limburg, the *Nationale Kalkmergelmaatschappij* NAKAM, which closed down in 1919 and was taken over by a Belgian company (Goudeau, 1997; Scharroo, 1946).

From 1917 on, governmental attempts were made to form a national cement industry which could compete with the prices of foreign cement. Research was carried out for a suitable location in terms of raw materials, lime and sea shells, and transportation. The first successful Portland cement factory on Dutch ground was *Eerste Nederlandse Cement Industrie N.V.* (ENCI, First Dutch Cement Industry), founded in 1926 in Maastricht (Heerding, 1971). Despite the name, the initiative for the company was Swiss-Belgian (Goudeau, 1997). The still existing factory was then one of the best equipped and largest Portland cement factories in Europe (Van der Schrier, 1938, 1951).

In the 1920s, the use of *hoogovencement* (blast furnace slag cement) was explored in the Netherlands and gradually accepted. As a result, the second main Dutch cement factory, *Cementfabriek IJmuiden N.V.* (CEMIJ, Cement factory IJmuiden, now ENCI-IJmuiden) was founded in 1930. CEMIJ produced *hoogovencement* (blast furnace slag cement) and *ijzerportlandcement* (Portland-slag cement), the Portland clinker was delivered by ENCI, and blast furnace slag by the Dutch steel factory Hoogovens (Anon., 1931).

In the 1930s, the Dutch cement market could be supplied with 50% of national cements. Four Dutch cement types were available: a normal Portland cement ENCI normal, a rapid hardening Portland cement Encielite, and as slag bearing cements *hoogovencement* and *ijzerportlandcement* (see Figure 3.6). In the following years, the national cement industry went into strong competition with the Belgian, German, English and French cement industries, leading to the *Vijflanden contract* (Five countries treaty). In this treaty, quota for import and minimum prices were regulated, and the Dutch companies were accepted as the leading ce-

ment companies in the Netherlands. With the Second World War the treaty was stopped by the Germans and at the end of the war, the Dutch cement production lay still (Heerding, 1971). ENCI and CEMIJ restarted their production in 1945, but until 1947 it was limited due to shortage of energy and packaging materials. In 1960, ENCI started with the production of *hoogovencement* in Maastricht (Jacobs, 1960; Van der Schrier, 1968). In 1963, another Dutch cement factory for *hoogovencement* was found as a cooperation between ENCI and Hoogovens: the *Rubor Cementfabriek Rozenburg N.V.* near Rotterdam (Heerding, 1971). The factory is now known as ENCI Rotterdam.

3.5 Quality and standardisation of cements used for historic concrete

Variations in the quality of cement have been already an early complain, and in the Netherlands the situation was aggravated by the fact that cements from different countries were used. Besides economic reasons tempting to tamper with the cement, the increasing scientific understanding of the correct composition of Portland cement, and influences on the performance of the cement led to changes in its composition. As most experience was gained with Portland cement, its composition was initially mainly discussed. In the following sections the main changes in composition due to increased insight into durability (Section 3.5.1), fineness of the cements (Section 3.5.2) and the introduction of standards for cement (Section 3.5.3) will be addressed.

3.5.1 Composition and durability

Natural cement is made by using rocks which have by nature a composition which would make a useable cement, although the composition could vary. For artificial cement the proportions have to be determined and a continuous quality of the cement is required. The main criteria are the workability, strength and durability of the cement.

The main raw material for Portland cement is limestone, which after burning will form into calcium oxide (CaO), silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3); the silicon dioxide and lime are necessary for hydration, whereas the aluminium and iron oxide are relevant during production. Magnesium oxide (MgO), sulphates (SO_3), and alkalis - sodium oxide (Na_2O) and potassium (K_2) - are present in the cement, originating from the used shale, clay or limestone. To improve the workability and avoid a too quick setting of the cement, gypsum (calcium sulphate, CaSO_4) is added as retarder.

With the increase use of Portland cement and observed durability problems, the composition of Portland cement was adapted throughout time. For example, in the 1880s in France and Germany, structures showed damage due to expensive reactions of the cement. As a consequence the use of pure Portland cement

was temporarily forbidden in Germany in 1885. The German Dyckerhoff carried out research and discovered that some of the concrete used had a high magnesia content. The cause was the use of sintered, magnesia containing Roman cement, which expands, contrary to Roman cement which had not been sintered. Research was carried out on the possible magnesium content of Portland cement, concluding that a magnesia content up to 5% was acceptable (Büsing & Schumann, 1905; Huberti, 1964; Stark & Wicht, 2001).

In the same period expansive reactions were observed when too much gypsum was used and a limit of 2% introduced (Büsing & Schumann, 1905). The underlying mechanism for this sulphate attack was discovered around 1890 by Michaëlis, who called the discovered reaction product *Zementbazillus*, currently known as ettringite (Stark & Wicht, 2001). A different expansive reaction was observed in the 1940s and first mainly in America; the identified cause was a reaction with some aggregates and the alkalis in the cement and named Alkali Aggregate Reaction (AAR) (Bogue, 1947). When using aggregates with reactive silica it is now recommended to use cements with low alkali content. In marine environments it was observed that Portland cement which had a high free lime content was more vulnerable, leading to the addition of blast furnace slag or trass to bind the free lime in the cement.

For the workability of the concrete the content of aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) had to be limited, as otherwise the risk of a too quick setting existed. The lime content varied during time as well, earlier cements with a lower content had lower early strength development. Higher lime content was only possible with higher kiln temperatures; otherwise, the cement needed to be ground finer to achieve higher early strengths (Bogue, 1947).

Not only the content of the individual constituents had to be determined but also their relationship. The hydraulic modules M for example described the proportions between calcium oxide (CaO), silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3), where suitable compositions had a value between 1.7 and 2.4 (Büsing & Schumann, 1905; Probst, 1935):

$$\frac{\% \text{CaO}}{\% \text{SiO}_2 + \% \text{Al}_2\text{O}_3 + \% \text{Fe}_2\text{O}_3} = 1.7 - 2.4 \quad (3.1)$$

Present day recommendations are M 1.8 – 2.2 (Benedix, 2008). The higher M is, the higher the hydration properties are, yet values above 2.4 were not desired as they had a too high lime content which could cause expansion reactions (Probst, 1935).

Another progress was the identification of the mineral phases formed in the Portland cement clinker. Several theories existed in the 19th century and in 1897 Törnebohm identified four mineral phases in the Portland cement clinker which he called alite, belite, celite and felite. In the 1930s Insley identified their composition: alite as tricalcium silicate 3CaOSiO_2 , in cement notation C_3S ; belite and felite as a dicalcium silicate 2CaSiO_2 or C_2S ; celite as calcium aluminoferrite (or

tetracalcium aluminoferrite) $4\text{CaOAl}_2\text{O}_3\text{Fe}_2\text{O}_3$ or C_4AF , and a new phase tricalcium aluminate $3\text{CaOAl}_2\text{O}_3$ or C_3A (Benedix, 2008; Bogue, 1947). The four phases C_3S , C_2S , C_4AF and C_3A are now used to describe the composition of cements. When partially hydrated or non-hydrated, these phases can be seen in petrographic analysis of the concrete and thereby can help to identify the used cement type (see Section 3.11).

3.5.2 Fineness of cement

Besides the choice of raw materials and their calcining, a third quality aspect is the fineness of the cement. Finer cements react quicker as they have more surface area and therefore can achieve earlier higher strengths. The requirements towards the fineness of the cement changed during time; initially, it was considered to have a cement as fine as possible, as coarse grains would not hydrate in the interior and only function as a fine aggregate (Memmler et al., 1907; Van der Kloes, 1893). Scharroo (1946) reflected on the development of the fineness of cement, and concluded that it was mainly influenced by the way the quality of concrete was evaluated, which was done by assessing the strength of the cement. A problem with too fine cements was that they are more prone to shrinkage. The tendency to ground cements finer continued into the 1960s, due to the pressure from the industry to increase the time of construction by allowing a quicker striking of the formwork. Another side effect of the finer grinding was that the concrete did not gain much in strength after 28 days, a characteristic which coarser ground cements had; additionally finer ground cements had less “reserves” to counteract the effects of carbonation and thus could be more vulnerable for carbonation induced corrosion (Grantham, 2011d).

The production of fine cements was not always easy and the fineness could vary depending on the country of origin. At the end of the 19th century, Van der Kloes (1893) commented that German, French and Belgian cements were able to fulfil the Prussian standards from 1887, English not. In this standard, less than 10% of the cement was allowed to remain on a sieve of 900 meshes/cm², in practice good cements left only 4%. References to German standards was necessary as the Dutch did not have own standards and definitions, and German cements were considered to be of a high quality.

At the beginning of the 20th century, the production quality had increased significantly. Most cements fulfilled or even surpassed the required values, and as a consequence the allowed maximum values decreased. Both, Dutch military guidelines from 1906 (Minister van Oorlog, 1906) and the first edition of the G.B.V. from 1912 require a value of 5% for a sieve of 900 meshes/cm².

In Table 3.3 an overview is given of the decreasing values for the required fineness of cement; later the fineness is differentiated according to the cement type with the introduction of Dutch standards for cement (Anon., 1927c). Whereas natural cements and slag-lime cements could be coarser, Portland cement, blast furnace and Portland-slag cement had to be finer and high-aluminium cement the

finest. The Blaine fineness, a present day indicator of the particle size of the cement, was not used in historic concrete textbooks or standards. An early Dutch mentioning is for Portland cement 2500 cm²/kg, for quick hardening Portland cement 5000 cm²/kg (Lambotte, 1965), modern cements have values between 3500 and 5000 cm²/kg (Nijland & Heinemann, 2008).

3.5.3 Introduction of standards

As no Dutch standards for cements existed at the beginning of 20th century and cements were imported from different countries, the Dutch cement market was chaotic: many actors tried to make profit, the foreign cements varied in properties, and fraud was not uncommon. Scharroo (1927e) criticised that the criteria to evaluate cements were not made by an independent and competent organisation. Scharroo considered the criteria mentioned in the G.B.V. 1918 as out-dated. In a survey carried out by Scharroo in the 1920s about the requirements for cements in tenders of 40 governmental projects, only one followed the requirements of the G.B.V. 1918, whereas all others neither followed the G.B.V. 1918, nor the new draft of the G.B.V., nor the draft of the cement standards; the demands in the tenders varied in compressive strength, tensile strength and fineness of the cements. Scharroo pled for unification, as the chaos affected badly the cement industry, hindering a consistency in the cement production, which was technically already possible. The situation could only be improved with the introduction of standards and if customers required the same type of cement. A draft for cement standards was published by scientists, producers and traders of such standards in 1927, and it was considered practical and realistic.

In 1929, first Dutch standards for cements were introduced: N 481 Portland cement, N 482 *Aluminiumcement* (high-aluminium cement or ciment fondu), N 483 *IJzerportlandcement* (Portland-slag cement), N 484 *Hoogovencement* (blast furnace slag cement), N 485 *Slakkencement* (slag lime cement), and N486 *Natuurcement* (natural cement) and later the N 618 for *Trasportlandcement* (Scharroo, 1942b). For Portland cement, *ijzerportlandcement* and *hoogovencement* two qualities were defined, Class A for normal cement and Class B for cement with an early high strength. In the standards the cements types, terminology and chemical composition was defined and the properties of the cements in terms of initial setting time, expansion, fineness and strength, and the packaging of the cement. These and other cements will be discussed in detail in the following Sections 3.6 to 3.10.

3.6 Portland cements

The basic principles for the production of Portland cement have not changed since Aspdin's patent in 1824. The two main ingredients of Portland cement are calcareous materials (limestone or chalk), and aluminium and silica containing

Table 3.3 Overview of required fineness of the cement.

(a) Portland cement; values indicate maximum percentage retained by part of weight.

	Prussian standards (Van der Kloes, 1893)	Dutch military Guidelines (Minister van Oorlog, 1906)	G.B.V. 1912	G.B.V. 1918
900 meshes/cm ²	10%	5%	5%	3%
4900 meshes/cm ²		30%	30%	25%

(b) Different standard cement types; values indicate maximum percentage retained by part of weight.

		900 meshes/cm ² N 480-d-0.210	4900 meshes/cm ² N 480-d-0.090
N 481 Portland cement			
1929		2%	20%
Scharroo (1945)	Class A	-	18%
	Class B	-	14%
N 483 <i>IJzerportlandcement</i>			
1929		2%	20%
Scharroo (1945)	Class A	-	18%
	Class B	-	14%
N 484 <i>Hoogovencement</i>			
1929		2%	12%
Scharroo (1945)	Class A	-	12%
	Class B	-	10%
N 485 <i>Slakkencement</i>			
1929		5%	-
Scharroo (1945)	Class A	18%	2%
	Class B	10%	1%
N 482 Aluminiumcement			
1929		1%	20%
Scharroo (1945)		14%	-
N 486 Natural cement			
1929		5%	-
Scharroo (1945)		-	5%
N 488 Trass			
1929		20%	
Scharroo (1945)		20%	
N 618 Trasscement			
Scharroo (1945)		8%	-

Note: 900 meshes/cm² $\approx$ N 480 - d-0.210 = 0.21 mm; 4900 meshes/cm² $\approx$ N 480 - d-0.09 = 0.09 mm.

clay or shale. The raw materials are ground, mixed and burnt to temperatures up to about 1450°C, when the materials sinter, and clinkers are formed. These clinkers are cooled and ground, and form the Portland cement; to control the binding time, gypsum is added. What did change is the quality of production and composition (see Sections 3.5.2 and 3.5.3). Besides normal Portland cement, special Portland cements with either special setting or hardening properties, and white Portland cement for aesthetical uses, have been applied in the Netherlands and will be discussed in the following sections.

3.6.1 Normal Portland cement

Portland cement was the most important binder for historic concrete, especially for reinforced concrete and was initially the only cement type allowed for such (Minister van Oorlog, 1906, G.B.V. 1912). At the beginning of the 20th century, the commerce with Portland cement was still innovative in the Netherlands. Doubts existed about this new, artificial cement. Other limitations for a wide application was its high price and therefore it was only used for special projects (Scharroo, 1946). When lower strength was required, in less severe environments or for plain concrete the use of inferior cements was suggested (Ast, 1907). The advantages of Portland cement which made it preferable to other cement types despite its higher price were its consistency in quality, its high strength, durability and especially its hydraulic properties. The dominant position of Portland cement is reflected in the former common terminology for cement and concrete; when no binder was explicitly mentioned, the use of a Portland cement was assumed (Scharroo, 1910a).

The application of Portland cement was mainly for reinforced concrete structures but was also advised for tampered concrete structures as only with Portland cement a sufficiently strong and lean concrete could be achieved (Van der Kloes, 1908c). Other non-structural use of Portland cement was for the fabrication of decorative elements, which were produced in the Netherlands from the middle of the 19th century (Stokroos, 1985), bedding mortars, floor constructions and plasters (Storm van 's Gravenzande, 1863). For the production of artificial stones, Portland cement was often used in combination with ground natural stone or pigments (Petry, 1913, see also Section 7.5).

To limit the fraud made with Portland cement and to protect the interest of the Portland manufacturers, definitions were made for the term Portland cement. A first was made in 1883 in Germany by the German Association of Cement Producers (*Verein Deutscher Cement-Fabriken*, from 1889 called *Verein Deutscher Portland-Zement Fabriken*). Portland cement had to be made from lime and clay, which should be calcined and sintered, and ground into a fine powder; the only allowed addition was gypsum with maximum 2% (Van der Kloes, 1893). In Dutch literature, reference was often made to the German definition as on the one hand a Dutch definition did not exist yet and on the other hand a large quantity of Portland cement used in the Netherlands was imported from Germany.



Figure 3.7 19th century Dutch advertisement for German Portland cement, emphasising that the cement has not been tampered with slags or limestone (1883, De Opmerker).

In the G.B.V. 1912, the main criteria for Portland cement were that the cement is artificial, its fineness and specific properties concerning strength and setting. In the second edition of the G.B.V. from 1918, the composition of the cement is for the first time prescribed by demanding a hydraulic modulus M of 1.7 (see Section 3.5.1). From the G.B.V. 1930 onwards, reference is made to the newly introduced standard for Portland cement, the N 481. Besides demanding a hydraulic modulus of 1.7, the maximum content of potential deleterious constituents is named: magnesium oxide (MgO) 3% and sulphates (SO_3) 2.5%. In the present day standard the limits are slightly higher. For Portland cement CEM I (NEN-EN 197-1:2000) a maximum content of 5% magnesium oxide (MgO) and 3.5% sulphates (SO_3), additionally a maximum chloride content of 0.10% is demanded.

In Table 3.4 an overview is given of the composition of some Portland cements discussed in Dutch literature. Due to the fact that many of the cements were imported from Germany and the influence of German literature, German Portland cements are commonly mentioned. In this table it can be seen that cements dating from the 19th century showed higher variations in composition and that from the 1930s on the values varied less. In general, the calcium oxide content increased with time, and the magnesium and sulphate content decreased, as already mentioned in Section 3.5.1. What also can be seen is that the iron oxide content increased with time, which could have caused a slight change in the colour of the Portland cement, making the cement darker.

Table 3.4 Overview of the composition of Portland cements discussed in Dutch literature. Percentage of constituents according to different references.

	Delfzijl cement, 1870s (Heerding, 1971)	Germany, 1883 (Scharroo, 1910a)	Germany, 1907 (Van der Kloes, 1908c)	unknown origin (Bergsma & Homan van der Heide, 1910b)	Germany (Scharroo, 1916)	Germany, 1919 (Van der Kloes et al., 1924)	unknown, possible Dutch (Bergsma, 1934)	High quality Portland cement (Bergsma, 1934)	Dutch ENCI (van Dijk & Van der Baan, 1952)	tendency
Calcium oxide (CaO)	54.1	58.22	57.72-67.60	59-65	60.84	54.42-67.47	61-65	61-65	66.5	↑
Silicon dioxide (SiO ₂)	28.2	19.8-26.45	17.23- 24.04	20-26	23.16	17.76-24.18	22	21	21.7	↑
Aluminium oxide (Al ₂ O ₃)	15.1	4.16-9.45	2.96-9.08	7-14	4.94	4.95-8.74	7	7	3.8	↑
Iron oxide (Fe ₂ O ₃)	2.6	2.19-4.47	1.23-4.62	7-14	2.61	1.27-4.08	3	3	3.8	↑
Magnesium oxide (MgO)	-	1 2.89	0.51-3.57	1-3	2.61	0.66-5.11	1.5	1.5	1.4	↑
Sulphates (SO ₃)	-	0.19- 2.19	0.88-3.30	<2	2.38	0.81-3.89	1.9	1.7	1.7	↑
Alkalis: sodium oxide (Na ₂ O) and potassium (K ₂)	-	0.19-2.19	0.23-2.01	<3	1	-	-	-	-	↑↓
Gypsum (CaSO ₄)	-	-	-	Not mentioned	-	-	-	-	-	↑↓

Legend: ↑ increasing ; ↓ decreasing; ↑↓ fluctuations.

When investigating historic concrete structures and the use of Portland cement is indicated in historic documents, it cannot be excluded that tampered cement was used, especially in the late 19th and early 20th century. As Portland cement was very expensive and the term not protected in the Netherlands, other products which were modified to look like Portland cement or natural Portland cement was sold as Portland cement (Boon, 1908; Büsing & Schumann, 1905). To reduce the production costs slags were added to Portland cement. Other known additives were grey limestone, shale, or poorer hydraulic limes with a high content of organic matter (Büsing & Schumann, 1905; Van der Kloes, 1893). A less mentioned modification to save costs was to use calcium carbonates originating from sugar refinery instead of lime (Rutgers, 1911). Especially Belgian cements had a bad reputation, not only in the Netherlands but also in Germany (see for example Ast, 1907). Advertisements emphasising the purity and manufacturing method of the Portland cement were not uncommon (see Figures 3.2 and 3.7).

3.6.2 Special Portland cement

Besides normal Portland cement, classified as Class A cement, a Portland cement with early high strength, was available, classified as Class B. Such cements were sold as *edcement* (“noble cement”), *supercement* or *groenstreepcement* (green stripe cement, referring to the green stripe on the cement bags, see Figure 3.8). The Dutch Portland cement factory ENCI produced an early high strength cement and sold it under the name *Encielite* (see Figure 3.6). Before the introduction of the classifications A and B in 1929, the cements were distinguished by calling it either *langzaam bindend* (slowly setting cement) and or *snelbindend* (quickly setting) (Boon, 1908; Scharroo, 1916). As the latter cement set too quickly it could not be used for normal concrete structures and was mainly advised for underwater placed concrete (Boon, 1908).

Early high strength Portland cement was already produced in the late 19th century but only after the First World War production was carried out on a wider scale. Early high strength was achieved by using carefully chosen raw materials, calcining them intensively and ground them finer than normal Portland cement, making it therefore more expensive (Probst, 1935). A cheaper method was to add accelerators to the cement. Examples are the German *höherwertige* (high quality) and *höchstwertige* (highest quality) cements with calcium chloride as accelerator (Scharroo, 1946). The use of chlorides as accelerators was ceased when it was understood that they can induce corrosion (see Section 5.4 *Admixtures and additions*).

A different special cement was rapid-hardening cement which was sometimes named a Class B cement (for example Bergsma, 1934; Boon, 1931; Scharroo, 1942a,b, 1946; Van der Schrier, 1938). In some cases a Class B cement was both rapid hardening and with an early strength. Rapid hardening cements were advised for bridges and civil structures where an early striking of the formwork was important to reduce the construction time and save formwork material (Probst,



Figure 3.8 Advertisements for groenstreep cement (Scharroo, 1930). a) Cover of the 1930 edition of the *beton-kalender* (concrete calendar) with a picture of the *groenstreep cement*. b) Advertisement from the Dutch cement syndicate: “Attention! Groenstreep cement [Green stripe cement] is German cement, sealed by the German factories in green striped bags.”

1935). In the 1960s, a Class C cement was sold with a very high early strength but it was not produced in the Netherlands (Van der Schrier, 1968).

3.6.3 White cement

White cement is now understood as a special, whiter Portland cement due to a lower iron oxide content, especially of the ferrite phase C_4AF , and manganese oxide. It was (and still is) more expensive than ordinary Portland cement as the production requires much higher burning temperatures (Cimenteries et Briqueteries Réunies N.V. (C.B.R.), 1934; Van der Vooren, 1931). White cement was used as a basis for coloured cement, since it is easier to colour and requires less colour pigments to achieve a good hue, yet lately replaced by blast furnace slag cement which has a rather homogenous light colour after oxidation (details for coloured concrete see Section 7.5.1).



Figure 3.9 Advertisement for the American white Portland cement "Wit Medusa" (N.V. Techn. Bureau v.h. Nierstrasz, 1931).



Figure 3.10 Advertisement for German Dyckerhoff Weiss (Van der Vooren, 1931).



Figure 3.11 Information brochure for the use of white cement by the Belgium company Cimenteries et Briqueteries Réunies N.V. (C.B.R.) (1934).

Historically, different types of white cement have been used, of which not all were similar to white Portland cement. At the beginning of the 20th century white cement could also refer to white gypsum which was used for interior plaster. As a basis for coloured concrete and natural stone imitations, magnesia cement could be used, which was by nature white, however its tendency for swelling limited its use. White cement similar to Portland cement was produced in the 1870s in Heidelberg, Germany; as raw materials local kaolin, white clay, and a local lime were used. The demand for the cement was limited and mainly used for the production of tiles. Other white cement types were made by adding gypsum and magnesium chloride, ammonium chloride, or calcium chloride (Scharroo, 1946; Van der Kloes, 1908c; Van der Kloes et al., 1924). The durability of such cements with high gypsum or chloride contents is however questionable. More successful was the production of white Portland cement in the United States of America at the beginning of the 20th century; the produced cement was then the highest quality white cement available (Scharroo, 1946). As white Portland cement was rather expensive, it was also tried to lighten up the colour of concrete made with normal Portland cement by adding slaked lime, white sand or ground marble (Büsing & Schumann, 1905).

Beside the American Medusa cement (Figure 3.9), European white cement was available in the Netherlands in the 1930s: the German Dykerhoff weiß (Figure 3.10), the Belgian C.B.R. extra blanc (Figure 3.11) and the British Snowcrete (Scharroo, 1946; Van der Schrier, 1938, 1942). The Belgian cement producer Cimenteries et Briqueteries Réunies N.V. (C.B.R.) (1934) (see Figure 3.11) advertised the advantages of white Portland cement as being superior to Portland cement in terms of durability and allowed an aesthetical use of exposed concrete; this cement was ground finer (3 – 5% on a 4900 meshes/cm² sieve), which was up to four times finer than a Portland cement of the Class B (see Table 3.3b).

The increased application of coloured decorative concrete in the 1920s and 1930s supported the use of white cement. After a period of limited availability in the years after the Second World War (van Dijk & Van der Baan, 1952), it was widely applied for decorative concrete elements in the Post-war reconstruction period (Ne., 1961). Further examples of the application of white Portland cement can be seen in Chapter 7.

3.7 Natural cement (*Natuurcement*)

Natural cement (*natuurcement*) is made from marls or clayey limestone which have by nature a composition similar to Portland cement and which are only calcinated but not sintered. Although the properties of natural cement are similar to those of Portland cement they show high fluctuations depending on the used raw materials. As even the properties of the raw materials originating from the same quarry differed, and as the rocks were calcinated in larger pieces, an equal distribution and quality control of the components was not possible. An improvement of the production methods to achieve a better quality was technically possible, how-

ever financially not attractive (Rutgers, 1911). These variations are still a reason why natural cements are seldom used nowadays (Neville, 2008). A comparison of natural cement originating from different countries cannot be directly made as their composition and properties are influenced by the properties of the regional marls (Hughes, Jaglin, Kozłowski & Mucha, 2009).

The differences in definition between natural cement, natural Portland cement and Roman cement have often been discussed. The term Roman cement (*romeinsch cement*, *Parker cement*) was already early on considered incorrect, and instead it should have been seen as a natural cement (Pasley, 1838; Taylor & Thompson, 1905; Vicat, 1837). In France, natural cement was seen as an “*intermediate between Roman and Portland*” (Taylor & Thompson, 1905, p. 48). From the middle of the 19th century with the introduction of Portland cement, the term natural Portland cement appeared, referring to natural cements which were in composition similar to Portland cement (Storm van 's Gravenzande, 1863).

Roman cement did not play a major role in the Netherlands, as its use had already passed its peak when the use of reinforced concrete commenced in the Netherlands, and for plain concrete lime and trass was used. According to Van der Kloes (1893), Roman cement was only seldom applied in the Netherlands, and if, it was used for water works. Another small area of application was for decorative prefabricated elements from the 1840s on (Stokroos, 1985). Its colour could vary between yellow, brownish-yellow and reddish (Ast, 1907).

Natural Portland cement was not appreciated for reinforced concrete, since its properties were not consistent, and no quality control was carried out, neither of the raw material (e.g. chemical analyses) nor of the production (Boon, 1913; Probst, 1917; Scharroo, 1916, 1927a). Natural cement was only shortly produced in the Netherlands in Vijlen (Felder, 2006). In Belgium its production was more common and sold under the French name *Ciment Portland naturels* (natural Portland cement). The main Belgian regions for the production of natural cement were the Walloon cities Tournai (Dutch *Doornik*) and Antoing (Rutgers, 1911; Scharroo, 1927a).

The use of natural cement for reinforced concrete was forbidden in the G.B.V., but its accidental use was known (Scharroo, 1927a). A major concern at the beginning of the 20th century was that Belgian natural Portland cement was sold as artificial Portland cement, not only to the Netherlands but also to Germany. To defend their leading market position which was suffering by the bad reputation the fraud had caused, the Belgian Portland cement producers addressed in 1908 the danger of such frauds in Germany and the Netherlands and advised the users to be cautious. The fraud with natural cement still continued in the 1920s, influencing the quality of concrete structures, but in general a decrease of its use was noticed (Scharroo, 1927a). Van der Kloes with his openness towards different binders was more positive about natural cements but admitted that bad experience had indeed caused a bad reputation (Van der Kloes, 1908c; Van der Kloes et al., 1924).

The inappropriate use of natural cement instead of Portland cement, and the

resulting poorer performance of a structure, or even damage, caused a bad reputation of concrete in general as the real cause, the use of the wrong cement type, was neglected. Besides an ignorance towards the differences between Portland cement and natural cement, the Dutch legal situation facilitated fraud. The G.B.V. 1912 did demand the use of artificial cements but did not give legal rights for the protection and definition of Portland cement. This was only possible with the introduction of the standards for Portland cement and natural cement in 1929, where an official distinction between the two cement types was made (Scharroo, 1927a). In the Dutch standard N 486:1929 for natural cement, similarities to Portland cement are admitted yet emphasis laid that the used raw materials are naturally premixed in rocks. Natural cements disappeared from Dutch concrete textbooks, and only occasionally mentioned in the reconstruction period after the Second World War where its use in case of emergency was justified, for example when it was not possible to obtain Portland cement quickly enough (van Dijk & Van der Baan, 1952).

3.8 Slag-bearing cements (*Cementen met Hooovenslakken*)

Slag-bearing cements are the second main group of cements besides Portland cement and will be discussed in this section. In the late 19th century it was discovered that some slags were latent hydraulic and could be used as an additive or even as a substitute for Portland cement. The slags commonly used for cements are by-products of the production of pig iron. In this period slags had become widely available with the increased iron production and the use of coke in blast furnaces. Factory owners searched to find economical solutions for a re-use of the slags, as a dumping of the slags due to their increased quantity had become difficult (Van der Kloes, 1900).

The German E. Lange discovered the hydraulic properties of ground granulated blast furnace slag in 1862. In 1878 it was used for the first time as an additive for Portland cement and in 1880 for slag-lime cement. In 1883, an application of slag-lime cement was presented during the Swiss national fair. In Germany this cement type was sold under the name *Puzzolancement* (Huberti, 1964); in the Netherlands it was known as *slakkencement* (see Section 3.8.1).

In Germany, discussions arose in the 1870s and 1880s, if added slag improved or degraded the quality of the Portland cement. In the 1880s, research was carried out in Switzerland by Prof. L. Tetmajer on the quality of cements when inter-grinding Portland cement and ground granulated blast furnace slag. Portland cement clinker was added as a catalyst as ground granulated blast furnace slag is only latent hydraulic. The new cement type was called *Eisenportlandcement* (Portland-slag cement, *IJzerportlandcement*, see Section 3.8.2), and was a blend of 70% Portland cement with 30% ground granulated blast furnace slag (Scharroo,

1946). Besides economic aspects of reusing a waste product, the better performance of slag bearing cements especially in marine environments led to substituting and blending of Portland cement with blast furnace slag cement.

The usability of slags is influenced by the cooling method after the slags are removed from the furnace. To achieve their latent hydraulic properties, a rapid cooling, usually by water cooling, is required. This rapid cooling causes a granulation of the slags. If slags are cooled too slow, they become grey-black and have little to no hydraulic properties (Anon., 1931; Benedix, 2008; Neville, 2008). Initially the rapid cooling of the slags caused problems but in the 1920s it was considered that these problems had been overcome and good slags were producible (Van der Kloes et al., 1924). In the first Dutch standards from 1929 for *hoogoven cement* N 484:1929 (blast furnace slag cement) and *ijzerportlandcement* N 483:1929 (Portland-slag cement) only the use of slags from the production of pig iron in blast furnaces was allowed.

Granulated blast furnace slag is alkaline and the main chemical constituents are calcium oxide (CaO), silicon dioxide (SiO₂), aluminium oxide (Al₂O₃), and magnesium oxide (MgO). In early definitions of slags, the proportions of the quantity of calcium oxide was not mentioned, for example Scharroo (1921, p. 282) defined it as the following :

$$1 \text{ part SiO}_2 + \text{Al}_2\text{O}_3 \leq 1 \text{ part MgO} \quad (3.2)$$

In the G.B.V. 1930, the composition of slags was prescribed as

$$\frac{\text{CaO} + \text{MgO} + \frac{1}{3}\text{Al}_2\text{O}_3}{\text{SiO}_2 + \frac{2}{3}\text{Al}_2\text{O}_3} \leq 1 \quad (3.3)$$

In the present day standard NEN-EN 197-1:2011 the composition of granulated blast furnace slag is defined as a combination of

$$\text{CaO} + \text{MgO} + \text{SiO}_2 \leq \frac{2}{3} \text{ and } \frac{\text{CaO} + \text{MgO}}{\text{SiO}_2} > 1 \quad (3.4)$$

A direct comparison of the two definitions is not possible, as the first does not include calcium oxide (CaO). However, it can be seen that the aluminium oxide (Al₂O₃) content is limited, when compared to the silicon dioxide (SiO₂) in the later formula. Comparing the values from 1931 to averages of present day granulated blast furnace slag (Neville, 2008) it can be concluded that especially the calcium oxide and silicon dioxide content increased (see Table 3.5).

Confusion occurred with the terminology of slags, influenced by foreign terminology and initially the secrecy of slag suppliers (Van der Kloes, 1900). The Dutch obsolete term for ground granulated blast furnace slag was *slakkenzand* (slag sand), and when finely ground it was named *slakkenmeel*. Van der Kloes (1900, 1911b) pointed out the confusion with the Dutch term *slakkenzand* with the German terms *Hüttensand* (literally “smelter sand”) and *Hüttenmehl* (fine ground *Hüttensand*), which refer to slags which has only been air cooled and not water

Table 3.5 Comparison of the composition of Portland cement and blast furnace slags (Anon., 1931). Values indicate percentage of the constituents.

	Portland cement (Anon., 1931)	Granulated blast furnace slags (Anon., 1931)	Granulated blast furnace slags (Neville, 2008)	trend
calcium oxide (CaO)	65	33	40-50	↑
silicon dioxide (SiO ₂)	21	33	30-40	↑
aluminium oxide (Al ₂ O ₃)	6	14	8-18	↑↓
iron oxide (Fe ₂ O ₃)	3	-		
iron oxide (FeO)	-	1		
magnesium oxide (MgO)	1	2	0-8	↑
gypsum (CaSO ₄)	2	-		

Legend: ↑ increasing ; ↓ decreasing; ↑↓ fluctuations.

cooled. Cements containing Hüttenmehl were produced for example in Belgium, by the Société Cockerill and sold as Cockerill-cement (Van der Kloes, 1911a,b; Van der Kloes et al., 1924).

The use of slag-bearing cements, even of slag as additives, was strongly discussed at the end of the 19th century. Van der Kloes (1893) admitted that good cement was possible when using alkaline slag, but described the doubts presented and lobbying by Portland-cement factory owners. Slag was cheap and available in a large quantity, in a time when the production of Portland cement finally had achieved a good quality after years of empiric and scientific research. Scientific doubts were grounded on the quality fluctuations of slags; known facts about the properties of slags, such as to use water cooled granulated slag, were concealed (Büsing & Schumann, 1905). Their composition could vary depending on the used iron ore and quantity of limestone, and possible high content of sulphide could cause degradation of the concrete (Ast, 1907; Rutgers, 1911). Only with a quality improvement of a former waste product to a good quality raw material, which required economic benefits for the iron producers, this problem could be overcome. The possibilities of producing a consistent quality by only using good slags from the same steel producer and by an automatic control of the mixing of Portland cement and slags was positively noticed by Rutgers during a site visit in Germany (1911). However, supporters of Portland cement vigorously defend the “pure” Portland cement, stating that any mixture with slags could only lead to a quality reduction of the cement and that users have to be informed when they bought such an inferior material (Büsing & Schumann, 1905).

A social problem with the acceptance of *ijzerportlandcement* (Portland-slag cement) was previous fraud by adding cheaper slag to Portland cement and selling it as normal Portland cement, facilitated by the similar appearance of Portland cement and slag. Testing for slags in Portland cement was time consuming and required experts, therefore it was strongly advised to control the packaging and producer. Yet, this was not always a guarantee as fraud was carried out in the factories as well (Bergsma & Homan van der Heide, 1910b; Rutgers, 1911). As testing possibilities the use of microscopy was advised and a visual inspection of

the colour of the fracture surface of concrete with a slag cement, which would be greener (Van der Schrier, 1938).

Difficulties in the acceptance of slag-bearing cements lay in the confusion of different cement types. A common misconception was between *slakkencement* (Section 3.8.1), which is a slag-lime cement, and *ijzerportlandcement*. Van der Kloes (1893) mentions anecdotes about frauds where slag containing cement was sold for high prices as Portland-cement. In the second edition of his book on mortars and concrete (Van der Kloes, 1908c), Van der Kloes is less negative about the common practice and more scientific when mentioning the origin and use of Portland-slag cements. Although referring to them as a “failed Portland-cement” (“*mislukte Portland cement*”, Van der Kloes, 1908c, p. 48), he mentions no further doubts concerning the use of slag, and their use and production had increased in the recent years; in Germany even a *Verein deutscher Eisen-Portland-Zement-Werke* (Association of German Portland-slag cements factories) had been founded. In the 1920s, a new slag bearing cement was introduced, supersulphated cement, which consisted mainly of ground granulated blast furnace slag and sulphate, and some parts of lime or Portland cement (see Section 3.8.4).

A turning point was the official acceptance of *ijzerportlandcement*; in 1909 it was put equal to Portland cement in terms of suitability in Prussia (Anon., 1910; Scharroo, 1946) but in the Netherlands it would take 20 years more. Although it was not mentioned in the G.B.V. 1918, its use was not explicitly forbidden in practice (Boon, 1920). More difficult was the acceptance of *hoogovencement* (blast furnace slag cement, see Section 3.8.3). With 70 – 85% of ground granulated blast furnace slag and only 15 – 30% Portland cement clinker it contained more of the “doubtful” raw material slag. In Germany, an association of the producers of blast furnace slag cement (*Verein deutscher Hochofenzementwerke*) was formed in 1913. In 1917, *Hochofenzement* (German for blast furnace slag cement) was considered equal to Portland cement in Prussia (Scharroo, 1946). In the G.B.V. 1930, a restricted use of *ijzerportlandcement* and *hoogovencement* was allowed and only in the 1962 edition they were put equal to Portland cement.

The increased scientific research on the properties of slag containing cements led to more insight into its resistance to sulphate attacks, which made them superior to Portland cement in marine environments (for example Boon, 1931; Probst, 1935; Ringers, 1924). The use of slag was not limited anymore by polemic prejudices, but supported by scientific insight. In present day concrete use, blast furnace slag cement (CEM III, see Table 3.1) is the most common cement with ground granulated blast furnace slag, besides Portland-slag cement (CEM II). For certain applications (e.g. marine environments) they are now considered superior to Portland cement.

3.8.1 *Slakkencement* (Slag-lime cement)

Slakkencement (slag-lime cement) contains 15 – 30% hydraulic lime and 85 – 70% blast furnace slag and no Portland cement. It was considered of a lower quality

than Portland cement (Foerster et al., 1912; Scharroo, 1916; Taylor & Thompson, 1905; Verhey, 1912). Its low price made it temporarily interesting for investigation as an alternative to Portland cement, as it would reduce the price of reinforced concrete (Christophe, 1905; van Rossum, 1902). Soon it was seen that this cement had inferior properties and therefore not advised to be used for reinforced concrete and seldom used for such. The problems were that it could not be stored for a long time, was susceptible to high shrinkage and perishable, it hardened poorly when exposed to air and was not durable in a marine environment. Although its tensile strength was reasonable, its compressive strength was below the strength of Portland cement (for example Boon, 1931; Christophe, 1905; Scharroo, 1921, 1946; van Rossum, 1902). A main producer was the Belgian Société Cockerill.

The use of slag-lime cements is mainly limited to the end of the 19th century, and later replaced with the successful production of Portland-slag cements, which were better in quality. Van der Kloes (1893) only quickly addressed the possibilities of using slag sand as a hydraulic binder for *slakkencement*; in the following edition (1908c) he stated that its production, at least in Germany, had been replaced by the production of *ijzerportlandcement* (Portland-slag cement).

Slakkencement, besides natural Portland cement, was considered as natural cement and often prohibited (for example Minister van Oorlog, 1906, G.B.V. 1912). In the period between the two World Wars, *slakkencement* was still mentioned as a precaution in textbooks of not to use this type of cement for concrete and not to confuse it with *hoogovencement* (blast furnace slag cement) (for example Bergsma, 1934; Scharroo, 1921). In Post-War textbooks on concrete *slakkencement* is not mentioned anymore (for example Van der Schrier, 1960). *Slakkencement* was regulated in the Dutch standard N 485:1929, with maximum content of 5% magnesium oxide MgO, 3% sulphates and should only be used for works of minor importance (Scharroo, 1942b; van Dijk & Van der Baan, 1952). In 1951, the name changed official to *slakkenkalk* (slag-lime) (Anon., 1951b).

3.8.2 *IJzerportlandcement* (Portland-slag cement)

IJzerportlandcement (Portland-slag cement, literally Iron-Portland cement, similar to the German term *Eisenportlandzement*) was the first slag containing cement which gained a wider acceptance. The Dutch term *ijzerportlandcement* did not indicate the use of slags as a raw material directly; contrary to the more obsolete Dutch term *Portland-slakken cement* (Van der Kloes, 1900). *IJzerportlandcement* contained up to 30% granulated blast furnace slag, which was interground with the Portland cement clinkers. An overview of the composition of *ijzerportlandcement* is presented in Table 3.6. Due to the admixture of blast furnace slags, the cement was able to bind free lime which made it suitable for marine environments.

Initially, doubts about the components of this cement were expressed. A cautious use was advised, as insight was missing into the durability of the reinforcement in concrete made with this cement. The previous fraud with Portland cement by adding slags and the difficulties to recognise the fraud, helped to support

Table 3.6 Overview of the composition of *ijzerportlandcement* in Dutch literature. Values indicate percentage of the constituents according to different references.

	Bergsma (1934)	Scharroo (1945)	Comparison with Port- land cement (Bergsma, 1934)
calcium oxide CaO	54-60	55-63	61-65
silicon dioxide SiO ₂	20-26	24-32	22
aluminium oxide Al ₂ O ₃		5-12	7
iron oxide Fe ₂ O ₃	9-15		3
magnesium oxide MgO	0.6-5		1.5
sulphates SO ₃	0.8-2.7		1.9
alkalis: sodium oxide Na ₂ O and potassium K ₂			-
gypsum CaSO ₄			

prejudices. The improved quality of the slags used and continuous chemical supervision reduced these doubts. In the Netherlands the use of *ijzerportlandcement* (Portland-slag cement) started in the 1910s (Boon, 1920) and its use was advised for foundations and heavy walls of hydraulic constructions, which did not require a high strength (Bergsma & Homan van der Heide, 1910a). *IJzerportlandcement* was not frequently used and only produced for a short time in the Netherlands (see Figure 3.6).

A first quality standard was introduced in 1909 in Germany to which Dutch textbooks referred to (Anon., 1910; Scharroo, 1921; Van der Kloes et al., 1924; Verhey, 1912). In the Netherlands the use of *ijzerportlandcement* was first allowed under restrictions for reinforced concrete structures in the G.B.V. 1930, and was defined in the Dutch standard N 483:1929.

3.8.3 *Hoogovencement* (Blast furnace slag cement).

Hoogovencement (blast furnace slag cement) appeared slightly later than *ijzerportlandcement* (Portland-slag cement) on the market and contained of 70 – 85% granulated blast furnace slag and 30 – 15% Portland cement. Not only the higher slag content distinguished *hoogovencement* from *ijzerportlandcement* but also the underlying concept of the function of the slag differed: whereas the function of the slag in *ijzerportlandcement* is mainly to bind excessive calcium oxide (CaO) and had the character of an additive, the slag functions as the main hydraulic component in *hoogovencement* and actively replaces parts of the Portland cement (Van der Kloes et al., 1924). The composition of *hoogovencement* can be seen in Table 3.7.

In Dutch textbooks *hoogovencement* is mentioned after the First World War (first mentioned in the following editions: Boon, 1920; Scharroo, 1921; Van der Kloes et al., 1924). As *ijzerportlandcement* had already paved the way for the acceptance of slag-bearing cements, *hoogovencement* was quicker accepted but initial doubts related to the higher slag content. Van der Vooren (1918) commented

Table 3.7 Overview of the composition of hoogovencement in Dutch literature. Values indicate percentage of the constituents according to different references.

	Bergsma (1934)	Scharroo (1945)	Comparison with Portland cement (Bergsma, 1934)
calcium oxide (CaO)	48-58	45-55	61-65
silicon dioxide (SiO ₂)	25-30	28-36	22
aluminium oxide (Al ₂ O ₃)	11-20	8-20	7
iron oxide (Fe ₂ O ₃)			3
magnesium oxide (MgO)	0.5-5		1.5
sulphates (SO ₃)			1.9
alkalis: sodium oxide (Na ₂ O) and potassium (K ₂)			-
gypsum (CaSO ₄)			

that with such a high slag content it would be of a too poor quality.

In Germany, *hoogovencement* - or using the German term *Hochofenzement* - was considered equal to Portland cement in 1917 (Scharroo, 1921). In the Netherlands its acceptance took longer; in the G.B.V. 1930 its use was allowed under restrictions, and only in the G.B.V. 1962 seen as equal to Portland cement.

The technical advantage of *hoogovencement* is that it is more durable in marine environments than Portland cement. In search of suitable cements the use of *hoogovencement* was investigated for the construction of the locks Noordersluis in IJmuiden and became the first major Dutch project using *hoogovencement* (see Section 3.3). As prejudices existed in the 1930s, the newly found Dutch *hoogovencement* producer CEMIJ carried out campaigns to inform people about this new cement (Heerding, 1971). The Netherlands became already in the 1930's a leading country for the use of *hoogovencement* for marine structures (Lea & Desch, 1935).

3.8.4 *Gesulfateerd cement* (Supersulphated cement).

Gesulfateerd cement (supersulphated cement) differs from *hoogovencement* (blast furnace slag cement) and *ijzerportlandcement* (Portland-slag cement) as it hardly contains Portland cement. Instead, it consists of a minimum of 75% granulated blast furnace slag, and 5 – 20% of gypsum or calcium sulphate to increase the hydraulic properties; other components are 5% of lime, optional Portland cement as activators for the hydraulic reaction. The calcium sulphate content varied during time: 5 – 7% (Scharroo, 1946), 6 – 8.5% (N.V. Ciments de Thieu, no publication date, after 1962), 5 – 12% (NEN 3550:1979), and in the present day standard 5 – 20% is required (NEN-EN 15743:2010). An overview of the composition of supersulphated cement is given in Table 3.8.

The advantages of a supersulphated cement are that it has an early high strength and is rapid hardening. Similar to other slag-bearing cements, supersulphated cement contains little calcium oxide (CaO), and has a better resistance towards aggressive environments. A later discovered advantage was the lower risk of Alkali-Silica Reaction (ASR). A down side was the tendency to powder at the surface, as ettringite, a main reaction product of this cement, dissolves when car-

Table 3.8 Overview of the composition of supersulphated cement in Dutch literature. Values indicate percentage of the constituents according to different references.

	Scharroo (1945)	N.V. Ciments de Thieu (no publication data; after 1962)	Comparison with Portland cement (Bergsma, 1934)
calcium oxide (CaO)	43.06	43.5-46	61-65
silicon dioxide (SiO ₂)	26.21	25-26	22
aluminium oxide (Al ₂ O ₃)	13.31	10-14	7
iron oxide (Fe ₂ O ₃)		0.7-1.5	3
magnesium oxide (MgO)		1.2-2	1.5
sulphates (SO ₃)	6.82	6-8.5	1.9
alkalis: sodium oxide (Na ₂ O) and potassium (K ₂)			-
gypsum (CaSO ₄)			

bonating at the surface, and therefore its use was discourage for exposed concrete (CUR report 36, 1966).

The production of supersulphated cement began in 1925 in France by *S.A. des Ciments Lorrains*. A Belgian supersulphated cement was produced by *La Louvière of Van de S.A. des Ciments de Thieu* and was sold as sealithorcement (N.V. Ciments de Thieu, sa; Van der Schrier, 1942). In Dutch textbooks it is discussed from the 1940s on (for example Scharroo, 1944; Van der Schrier, 1942). Although already available from the middle of the 1920s, supersulphated cement is not mentioned until the 1962 edition of the G.B.V, where a restricted use is permitted. It was standardised in 1953 in the N 1591:1953.

A similar cement was the German *Gipsschlackenzement* (“gypsum-slag cement”) which was standardised in Germany in 1944 and in 1954 renamed in *Sulfathüttenzement* (Huberti, 1964). It was based on ground granulated blast furnace slag with additions of 10% gypsum and 5% Portland cement. Without the addition of Portland cement it was known as *Gipsschlackebinder*. Its production required less coal than for Portland cement, a characteristic which was important in the first years after the Second World War (Wendehorst, 1949).

3.9 Pozzolanic cements

Besides the two main groups, Portland cements and slag bearing cements, pozzolanic cements were occasionally used for historic concrete. Their use and history precedes those of the previously mentioned cements.

Pozzolanic materials usable for cement production, both natural and artificial, can be used for the production of cements when finely ground. They consist of mainly reactive silicon dioxide (SiO₂) and aluminium oxide (Al₂O₃). As natural pozzolanas “*materials of volcanic origin or sedimentary rocks with suitable chemical and mineralogical composition*” can be used (NEN-EN 197-1:2000). Natural pozzolana was already used in combination with lime for the Roman *opus caementicium* (see Section 1.2). Traditionally, trass (Section 3.9.1) and for a short

while *Amsterdamsch cement* made from silt from the sea, was used as natural pozzolana in the Netherlands. Historic, artificially produced pozzolanas were brick powder; a more recent artificial pozzolana is fly ash (Section 3.9.2). Occasionally, ground granulated blast furnace slag was considered as an artificial pozzolana (van Dijk & Van der Baan, 1952).

3.9.1 Trass and trass bearing cements

Trass is a natural pozzolana and has latent hydraulic properties. Only when used together with an activator such as Portland cement or lime, a hydraulic reaction will take place (Trassforschungsinstitut der Tubag Andernach a. Rh., 1934; van Dijk & Van der Baan, 1952).

Trass has been introduced in Northern Europe already with the Roman Empire, after discovering the pozzolanic properties of ground tuff stone from the German Eifel region. With the decline of the Roman Empire, the use of trass decreased. Only in 17th century the benefits of using trass for hydraulic structures was rediscovered by the Dutch. In the Netherlands, German Rhenish trass from the Eifel region was used (Figure 3.12). In Table 3.9 an overview is given of the composition of German trass.

The use of trass for mortars had a long tradition in the Netherlands, and initially it was used for plain concrete structures such as for abutments, locks and foundations. The binder was often a mix of trass and lime, and resulting concrete named *trasbeton* (Boon, 1908). Plain concrete with trass was often made with broken bricks as aggregates (see also Heinemann et al., 2012), in Dutch known as *brikkenbeton*.

Traskalkbeton (trass-lime concrete) was made with lime, for example shell lime, and trass. It was used for plain concrete structures, especially for hydraulic, underwater and military structures as it was durable in marine environments and had good resistance towards shocks and settlement (Dwars, 1923; Hambloch, 1918; Trassforschungsinstitut der Tubag Andernach a. Rh., 1934). In the Dutch military guidelines from 1906, the use of a trass-lime cement was advised for plain concrete structures (Minister van Oorlog, 1906). Concerns did exist of using a trass-lime cement for mass-concrete structures as it did not harden in the core of a thick structure as the required air for hardening could not reach it. Additionally, it could be more prone to freeze-thaw damage (Ast, 1907). On the other hand, its low hydration heat made it suitable for mass concrete (Trassforschungsinstitut der Tubag Andernach a. Rh., 1934).

Trass and Portland cement went into competition, and trass producers advertised its advantages over Portland cement (Herfeldt, 1884; Trassforschungsinstitut der Tubag Andernach a. Rh., 1934). Van der Kloes (1893; 1908c; 1924) favoured the use of trass for concrete works when the slower hardening of trass cement did not matter, as it was cheaper than Portland cement. Other considered its slower binding time and lower strength than Portland cement as an argument for not using it for reinforced concrete (Boon, 1908). With the advent of Portland cement



Figure 3.12 Dutch advertisement for German Rhenish trass (Trassforschungsinstitut der Tubag Andernach a. Rh., 1934).

Table 3.9 Composition of German Trass. Values indicate percentage of the constituents according to different references.

	Trassforschungsinstitut der Tubag Andernach a. Rh. (1934)	Bogue (1947)	Van Dijk & Van der Baan (1952)
calcium oxide (CaO)	1.33-3.28	2.6	3-12
silicon dioxide (SiO ₂)	56.42-66.10	55.2	46-59
aluminium oxide (Al ₂ O ₃)	10.48-19.39	16.4	10-19
iron oxide (Fe ₂ O ₃)	3.95-4.68	4.6	4-12
magnesium oxide (MgO)	0.66-1.83	1.3	1-7
sulphates (SO ₃)	0-0.38	0.7	-
alkalis sodium oxide (Na ₂ O)	2.23-3.92	4.3	3-10
potassium (K ₂)	2.81-3.26	5.0	3-10

and reinforced concrete, the use of trass declined. A revival of trass was caused by the insight that Portland cement is not durable in marine environments. The upcoming of slag-bearing cements which were durable in marine environments as well, caused a decline of trass cements again (Trassforschungsinstitut der Tubag Andernach a. Rh., 1934). The Netherlands was known as one of the European countries, besides Belgium and Germany, to add trass for hydraulic and marine structures (Probst, 1917). For *trascementbeton* (trass-(Portland)cement concrete)

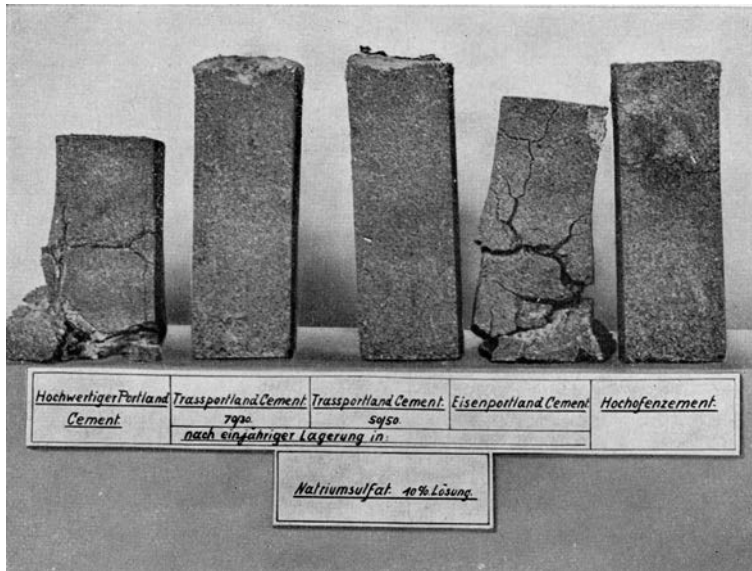


Figure 3.13 Experiments carried out by Tuffstein- und Basaltwerke A.G. to test the resistance of different cements by submerging the samples one year into 10% sodium-sulphate solution, showing that trass bearing cement and blast furnace slag cement perform the best. From left to right: high quality Portland cement, trass-Portland cement 70 PC/T, trass-Portland cement 50/50, Portland slag cement and blast furnace slag cement (Trassforschungsinstitut der Tubag Andernach a. Rh., 1934).

a blend of Portland cement and trass was used. It was recommended when the initial strength of a lime-bearing trass cement was insufficient and the environmental class of the concrete structure was not suitable for a pure Portland cement (Trassforschungsinstitut der Tubag Andernach a. Rh., 1934). An artificial trass was patented in 1919 in Germany, respectively in 1922 in the Netherlands, based on a mixture of half slags and half burnt clay but not widely applied (van Dijk & Van der Baan, 1952). Initially, discussions arose whether trass is a substitute for Portland cement or only an additive, whereas latter became the common concept (Scharroo, 1946).

Research on the suitability of adding trass to Portland cement in marine environments was investigated in the late 19th century (Ast, 1907; R., 1896). Trass was added to Portland cement to improve the durability, as it bound the free lime in the cement, thus limiting leaching, decreased the permeability and increased the resistance towards acids and salts. These modifications made this cement more suitable for marine and peat environments where the risk of sulphate attack existed (see Figure 3.13). Trass was also added for concrete sewage pipes and in peat bog environments. For construction, the advertised benefits were based on the slower pozzolanic reaction which improved the bond of construction joints,

Table 3.10 Applied mixtures of trass and different binders (Trassforschungsinstitut der Tubag Andernach a. Rh., 1934).

Type of binder	Binder content %	Trass content %
Portland cement	70-50	30-50
Ijzerportland cement (Portland-slag cement)	80-60	20-40
Hoogovencement (Blast furnace slag cement)	85-70	15-30
Eminently hydraulic lime	50	50
Feebly hydraulic lime	50-35	50-65

reduced the risk of segregation, had a better workability and created a smoother surface. Such aspects were relevant as in the first decades of the 20th century concrete was still manually compacted. Concerns were raised that trass could decrease the bond between the cement and the reinforcement, yet tests showed that the bond was equal to when using Portland cement (Boon, 1920, 1931; Probst, 1935; Trassforschungsinstitut der Tubag Andernach a. Rh., 1934; Van der Schrier, 1938). In recent recasting experiments to understand the properties of historic concrete made with Portland cement and trass could not confirm all assumed advantages of adding trass but, among other effects, what could be seen in that the concrete is denser (Nijland, Larbi, de Rooij & Polder, 2007).

The use of trass as an additive for other cements such as *hoogovencement* (blast furnace slag cement) was controversial. On the one hand it was not considered useful, as these cements had a low calcium oxide (CaO) content and thus already durable in marine environments (Probst, 1935); on the other hand, it also increased the elasticity and reduced the permeability, segregation and the heat development during hydration, thus trass was occasionally advised for slag bearing cements (see Table 3.10) (Burchartz et al., 1927; Trassforschungsinstitut der Tubag Andernach a. Rh., 1934).

Large scale tests on the durability of cements in brackish and sea water were carried out as part of the research prior to the construction of the locks in IJmuiden, including samples with trass-cement, Portland cement and the recent *hoogovencement*, whereas the latter appeared to be the most suitable (Ringers, 1924). For the construction of the locks of the Buitensluishoofd, sheds for the storage of trass, and the use of a trass-cement with 75% trass is described (Visser, 1927a,b). A detailed description is given of the on-site mixing of the cement with the trass before mixing the cement with the aggregates, which allowed a good control of the quantity of cement and trass. However, research carried out on a different part of the lock, the *Noordersluis* (Northern lock), which was assumed to be constructed with a similar trass-cement, gave no clear evidence for the use of trass, possible due to difficulties to identify trass after such a long time (Nijland et al., 2007).

Initially, trass was mixed on-site with the Portland cement. The Dutch contractor H.F. Boersma protected trass-cement by patent already in 1912 for England, France, Belgium and the United States; however it was not until 1929 that the German factory Tuffstein- und Basaltwerke A.G. (now known as tubag) brought

Table 3.11 Overview of the composition of different mixtures of trass-Portland cement discussed in literature. Values indicate percentage of the constituents according to different references.

	30 T/70 PC (Bergsma, 1934)	30 T/70 PC (Bogue, 1947)	50 PC / 50 T (Bergsma, 1934)	50/50 mix (Bogue, 1947)
calcium oxide (CaO)	50	46.8	40	35.3
silicon dioxide (SiO ₂)	29	22.3	34	25.1
aluminium oxide (Al ₂ O ₃)	10	8.3	12	8.9
iron oxide (Fe ₂ O ₃)	4	2.5	4	3.3
magnesium oxide (MgO)	-	1.9	-	1.2
sulphates (SO ₃)	-	1.8	-	1.1

a factory blended trass-cement on the market. In the late 1920s, factory blends were sold, for example *trasportlandcement* (trass-Portland-cement), where the trass and Portland cement had been interground. Initially, two mixtures were available: 30% trass and 70% Portland cement, 50% trass and 50% Portland cement, later also with 40% trass and 60% Portland cement (Bergsma, 1934; Scharroo, 1946; Trassforschungsinstitut der Tubag Andernach a. Rh., 1934; Van der Schrier, 1938). Present day trass cement (Portland pozzolana cement) has a trass content of 6 – 35% (Wendehorst, 2004) and it is considered that a trass content of at least 30% can be beneficial for the prevention of ASR (Nijland et al., 2007). In Table 3.11, an overview is given of different mixtures of trass-Portlandcement.

As the trass was interground with the Portland clinkers, the quality of the mixture was better and was initially advised. Later it was advised to add the trass to the cement, which allowed a free choice of trass content (compare different editions of Van der Schrier, 1938, 1968).

The quality of trass was distinguished by its colour of the used tuff; a blue tuff gave the best quality whereas grey and yellow tuff gave lower quality (Scharroo, 1945). In 1929 the Dutch standard N 488 was introduced (Scharroo, 1942b). The required fineness was with maximum remains of 20% on sieve with 900 *meshes/cm*², 10% was possible; the 20% mark is identical with the fineness required in the German trass standards from 1908 and 1926 (L. M., 1926). In 1943, it was standardised as the N 618:1943 (Scharroo, 1946) and a restricted use allowed the G.B.V. 1962.

Trass-cement was widely used for marine structures, but was replaced by *hoo-govencement* with time (Van der Schrier, 1968). Known Dutch examples for its application are the tampered concrete in Scheveningen's harbour, the north sea channel IJmuiden, some bridges over the Meuse, a trass-lime concrete for a bridge in Katerveer, and a trass-lime cement concrete for the bridge over the Oude Maas in Spijkernisse (Trassforschungsinstitut der Tubag Andernach a. Rh., 1934). Van Rossum (1902) described the mix of the concrete blocks used in Scheveningen's harbour with 1 part cement: $\frac{1}{2}$ part trass: 3 parts sand: 5 parts gravel. The last known Dutch application of trass cement was in the 1970s (Nijland et al., 2007).

3.9.2 Fly ash cement (*Vliegas cement*)

Fly ash is a combustion residue with pozzolanic properties of the coals burnt during the production of electricity. Its period of use as a pozzolanic additive falls outside of the period of historic concrete investigated in the Netherlands but it should be mentioned that its development does lie within this period. Its use as a substitute for Portland cement was already investigated in Germany during the 1920s, leading to first applications in the 1930s in Germany, England and the United States of America. Its use was discussed in the period after the Second World War, including in the Netherlands. By then, fly ash had become wider available due to the increased use and production of electricity, and the prices for Portland cement were high. However, the quality of fly ash still varied strongly, as it was influenced by the combustion type and impurities of unburnt coal. Nevertheless, a potential of using fly ash as an pozzolanic additive for cement was proven (Leeuw, 1955). It was not until the late 1970s that the use of fly ash for cement was wider discussed and researched in the Netherlands (Theissing, 1982). Fly ash cement is now worldwide the most common artificial pozzolana for concrete (Neville, 2008).

3.10 Other cements

Besides the previously mentioned groups of cement used for historic concrete - Portland cements, natural cement, slag-bearing cements and pozzolanic cements - other cements were applied or at least discussed in the Netherlands. Some were similar to the standard cements yet sold under brand names (e.g. Ferrocrete, a English rapid hardening cement) or were cements for special non-structural uses (e.g. asbestos cement, see also Scharroo, 1942b). Some cements had specific compositions, but did not play a major part in the history of cements in the Netherlands, such as the Silico cement (a blend of Portland cement with quartz sand, which are ground finely together) (Van der Kloes, 1908c; Van der Schrier, 1938, 1942, 1953). In the following section, two cements which are often mentioned in historic concrete literature are described: *ertscement* (Iron-ore cement) and aluminium cement (high-aluminium cement). Cases of their use in the Netherlands have not been traced back yet but their use is not excluded, especially as they were commonly mentioned in textbooks dating from the 1930s onwards.

3.10.1 *Ertscement* (Erz cement)

Ertscement (Erz cement, iron-ore cement) is a brownish cement where the aluminium oxide has been replaced with iron oxide (see Table 3.12). It is characterised by its high resistance towards sulphate attack which made it suitable for marine and peat environments (Probst, 1935; Van der Schrier, 1938, 1942). *Ertscement* was twice as expensive than Portland cement (Kommerell, 1917), but still cheaper than aluminium cement (see Section 3.10.2) and therefore advised as a substitute for the latter (van Dijk & Van der Baan, 1952).

Table 3.12 Overview of the composition of *erts cement* (Erz cement) discussed in literature. Values indicate percentage of the constituents according to different references.

	Anom. (1904)	Van der Kloes (1908)	Van der Kloes, et al. (1924)	Bergsma (1934)	trend
calcium oxide (CaO)	62.4-65.5	63.5	54.42 - 67.47	63	
silicon dioxide (SiO ₂)	19.9 -23.8	19.5	17.76 - 24.18	23	↑
aluminium oxide (Al ₂ O ₃)	1.6 -4.4	3.5	4.95 - 8 .74	2.75	↑↓
iron oxide (Fe ₂ O ₃)	7.8 11.1	9.4	1.27 - 4.08	5.75	↓
magnesium oxide (MgO)		0.2	0.66 - 5.11	1.7	↑
sulphates (SO ₃)	0.6-1.2		0.81 - 3.89	1	↑↓
alkalis					
gypsum (CaSO ₄)		2.2			

The Germans Michaëlis and Schott discovered independently the possibility to replace aluminium oxides with iron oxides in the 1870s, yet its production was still difficult. A first patent, naming the cement *Erzzement* (in German), was obtained together by Michaëlis and a German Portland-cement factory in Hemmoor in 1901. A wide application for concrete was hindered due to production difficulties and high production costs, and poorer workability.

Concrete made with *erts cement* was too lean and its setting too slow (Ast, 1907; Van der Kloes, 1908c; Van der Kloes et al., 1924). With the improvement of the production methods, the initially criticised inactivity during setting was overcome (Burchartz et al., 1927). In the Interwar period (see also advertisement in Figure 3.3), the use of *erts cement* was justified as it had a good resistance towards chemical attack and its price was lower than of the recent high-aluminium cement. Advised uses were for reinforced concrete chimneys (see for example Bergsma, 1934). It was not widely applied and disappeared from textbooks during the 1950s (compare Van der Schrier, 1953, 1960). It was not mentioned in the G.B.V. and not produced in the Netherlands (van Dijk & Van der Baan, 1952).

3.10.2 *Aluminium cement* (High-aluminium cement)

Aluminiumcement (High-aluminium cement, calcium aluminium cement) differs from Portland cement both in the used raw materials and in production. Its several synonyms are based on its different production technique and raw materials. The French terms *ciment fondu* and *ciment électrique* indicate that the raw materials are melted in electrical ovens. Commonly used Dutch synonyms were *aluminiumcement*, *alcement*, *smeltcement*, *ciment fondu*, *electrocement*, *Lafarge-cement* (Betonvereniging, 1929; Boon, 1931; Scharroo, 1942b; Van der Schrier, 1938). The scientific basis for using aluminium for a hydraulic binder was already laid in 1906 by the German O. Schott's dissertation about the hydraulic properties of lime-silicate and lime-aluminate. In 1908, the French J. Bied invented aluminium cement, using limestone and bauxite and melting them together. A wide-scale production and application only started in the Interwar period. Initially, it was produced under the name *ciment fondu* by the French company S.A.

Table 3.13 Overview of the composition of aluminium cements discussed in literature. Values indicate percentage of the constituents according to different references.

	Van der Kloes, et al., (1924), Van Dijk & Van der Baan (1952)	Bergsma (1934)	Probst (1935)	Scharroo (1946)	ISTRA 40 (CALCUCEM, 2010)	trend
calcium oxide (CaO)	40	35-45	35-40	35-40	37-40	
silicon dioxide (SiO ₂)	10	5-10	10-12	10-12	≤6	↓
aluminium oxide (Al ₂ O ₃)	40	35-55	40-45	40-45	38-42	
iron oxide (Fe ₂ O ₃)	10	5-15	1-20	10-15	13-17	↑
magnesium oxide (MgO)					<1.5	
sulphates (SO ₃)					<0.4	

des Chaux et Ciments de Lafarge et du Teq te Viviers. Later it was produced in Switzerland, Germany and in the USA as well (Probst, 1935). It was permitted with restrictions from the G.B.V. 1930 onwards and standardised as N 482:1929.

For the production of aluminiumcement limestone and components with a high aluminium oxide (Al₂O₃) content, such as the aluminium ore bauxite (Al₂O₃ + 2 H₂O), are used. From 1940 onwards, artificial bauxite was used as well (Scharroo, 1946). The raw materials are ground together and melted at 2000° C (Van der Schrier, 1951, 1968). The colour of aluminiumcement is rather dark, steel-grey to blue-black (Probst, 1935; Van der Schrier, 1938).

Aluminiumcement has a low calcium oxide (CaO) content and is therefore very durable in aggressive environments (see Table 3.13). It was seen as promising cement: it reached after 24 hours a strength for which Portland cement would require 4 weeks, it had a total resistance towards sulphate attack and sea water, and considered as a cement of very high quality (Betonvereeniging, 1929; Boon, 1931). A wide-scale application was prevented because of its very high price due to the production method, which was up to three to four times the price of Portland cement (Probst, 1935; Van der Schrier, 1938; van Dijk & Van der Baan, 1952). Due to the high price, it was sometimes blended with quartz sand, but still achieved a reasonable high strength. Besides its application for aggressive environments, its used was advised when a very early removal of the formwork was necessary (Anon., 1927a; Van der Kloes et al., 1924). A more common use was for the casting of anchors when placing machinery. Its high heat development during hydration allowed its use for temperatures down to -15° C (Van der Schrier, 1938, 1968). Its resistance to very high temperatures favoured its use for prefabricated insulating concrete elements to protect structures exposed to very high temperatures (Bond van Fabrikanten van Betonwaren in Nederland, 1957, 1964).

Aluminiumcement has the disadvantage of losing strength after time, also known as conversion phenomenon, which led to structural failures (e.g. in the United Kingdom) (Broomfield, 2003). Nowadays, not the early but only the later high strength is considered when using aluminiumcement. Its main present day use is for non-structural elements exposed to aggressive environments (e.g. industrial environments).

3.11 Identification of the used binder

Gaining historic information on the used binder is relevant in the conservation process. However, it is still common practice of not carrying out detailed investigations of the binders.

First, identifying the binder gives historic information and helps to understand the underlying development of cement applications. This includes identifying rarities, novelties in application, special design intentions or characteristics of a construction period. Such information can be used when evaluating the heritage value related to the historic concrete.

Second, such information is relevant for the technical aspects of the conservation process. Understanding the composition of the concrete, including the binder used, can help to identify the presence and cause of degradation mechanisms. The identification of the binder used and the composition of the concrete is necessary in order to choose a compatible repair mortar (see Chapter 9 *Impact of repairs on historic concrete and heritage values*).

For preliminary information acquisition, the construction period (see also Figure 2.13 *Timeline for binders used for historic concrete*), the building typology, the use of plain or reinforced concrete, and the environment the structure was initially exposed to, can give first indications. In historic documents such as tenders, the intended binder type can be mentioned, but it has to be kept in mind that especially in the late 19th century and the first decades of the 20th century fraud was not excluded. For an exact identification of the used binder, their chemical composition must be identified by further material research.

Depending on the research questions during investigation, different techniques can be applied for the identification of the used binders. Details and limits of different investigation methods to investigate concrete and historic mortars have been previously published and can be referred to during investigation (for example Eden, 2011; Middendorf, Hughes, Callebaut, Baronio & Papayianni, 2005a,b; Nijland & Larbi, 2010; van Balen et al., 2003; Varas, Alvarez de Buergo & Fort, 2005).

Common techniques are the combination of chemical analysis with microscopic analysis, such as polarizing and fluorescent microscopy (PFM) (see for examples Figures 3.14 to 3.17). A chemical analysis can give quantitative information of the materials used, and optical microscopy, also known as concrete petrography, can give qualitative information, such as the relationship between the different constituents (e.g. interface of aggregate and binder), information on degradation and ageing (e.g. carbonation, cracking) (Nijland & Larbi, 2010). To carry out such investigations, an experienced examiner is required, especially for historic concrete as their composition deviates from modern concrete. Some cements are not frequently encountered and little reference works exist on the petrography of historic concretes.

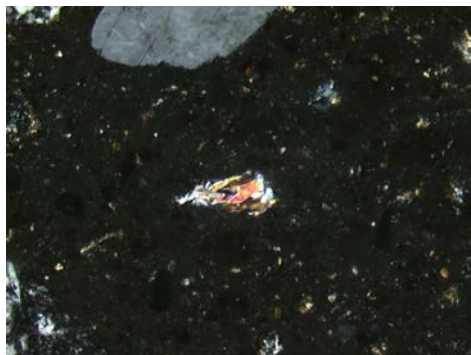


Figure 3.14 Photomicrograph (100x, cross polarised light) showing Portlandite which indicates that the binder is Portland cement (Fort Bezuiden Spaarndam, 1897-1901), image by T.G. Nijland.

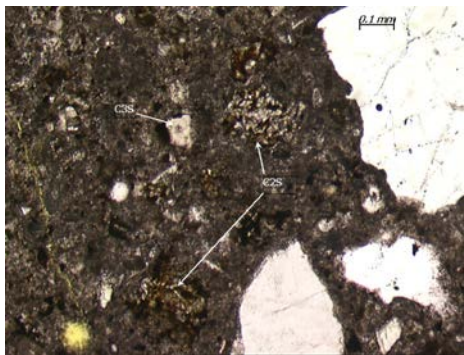


Figure 3.15 Photomicrograph (100x, plain polarised light) showing coarse Alite C_3S and Belite C_2S indicating coarse ground Portland cement (Fort Bezuiden Spaarndam, 1897-1901), image by T.G. Nijland.

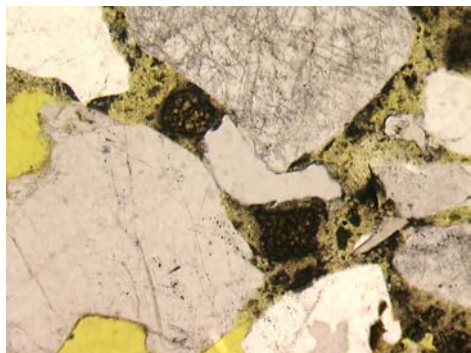


Figure 3.16 Photomicrograph (100x, plain polarised light) showing coarse C_2S (sample from the Betondorp, 1920s, details of building and location unknown), image by T.G. Nijland.

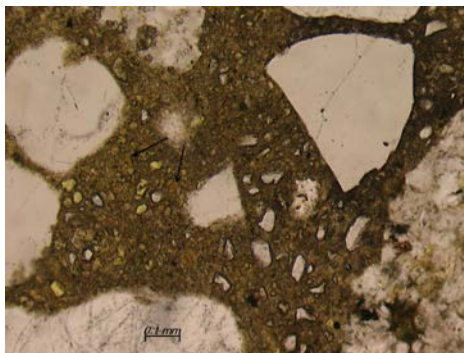


Figure 3.17 Photomicrograph (100x, plain polarised light) showing blast furnace slag indicating the use of a blast furnace slag cement (Pumping station Parksluizen, Rotterdam; G. J. Van der Grinten, 1967), image by T.G. Nijland.

The following techniques can be applied but are in practice less common and should be considered when chemical and petrographical analyses do not give sufficient answers. X-ray diffraction (XRD) can be employed for the identification of binders used, the mineral phases, and crystalline aggregates but not organic constituents. Scanning electron microscopy (SEM) can be used to analyse the microstructure and if equipped with an X-ray spectrometer (EDX) the chemical elements can be identified. As the resolution is higher than with a petrographic analysis, finer binders can be identified. Fourier transform infrared spectroscopy analysis (FTIR) can give qualitative information of the chemistry and can identify organic components.

The investigation of historic mortars and cements can be challenging, also as limited reference material exists for investigators on the various properties and details of historic cements. The various production methods (calcinating, sintering, melting) can be used as an indication of the examined cement as the different temperatures can lead to the formation of different mineral phases in the cement. For example, research has been carried out to distinguish between natural and Portland cement (Callebaut, Elsen, Van Balen & Viaene, 2001; Varas et al., 2005). The main indication derives from the different burning temperatures of natural and Portland cement, whereby they consist of different mineral phases. Natural cements, which are burnt at lower temperatures, have mainly C_2S (belite) with only local areas of C_3S (alite) due to local higher burning temperatures, Portland cement mainly consists of C_3S , yet the main distinguishing feature is the presence of the mineral gehlenite (C_2AS) and calcite ($CaCO_3$) in natural cement (Callebaut et al., 2001; Varas et al., 2005).

The understanding of the historical context, and the location of the building (e.g. near seawater) can give an indication of what could be the possible binder, guiding the investigation. However, the mind has to be kept open for “surprises”, especially for concrete dating from the 1930s and earlier. The surprises could be the use of a natural Portland cement instead of an artificial Portland cement, other indications of former frauds such as the presence of slag in cement which should have been a Portland cement, or special blends with trass or lime.

3.12 Conclusions

In this chapter it was shown that several binders have been used for historic concrete in the Netherlands, with initially Portland cement and later *hoogoven cement* (blast furnace slag cement) as main cements. Some cements mentioned will have only been applied occasionally or for a limited period of time. Traditional binders such as hydraulic lime and trass have been used for plain concrete in the 19th century as well, an aspect which is often forgotten when reviewing historic concrete.

The use of the different cements is, in the major aspects, similar to the use in other countries in terms of moment of introduction, indications of application, regulation and improvement of quality. However, as the Netherlands were not a

centre for cement research and production, this occurred sometimes later than in other countries, such as Germany which was leading at the beginning of the 20th century. Specific Dutch characteristics can be encountered as well. One example originates in the traditional use of trass and the need for hydraulic structures, leading to the preference of adding trass to concrete for marine structures. As the Netherlands initially did not have its own cement industry, imports from several countries were necessary, leading to a wider variety of the properties of the cements used. The properties of the different binders changed during time as well as in terms of chemical composition and fineness which can affect their durability and resulting in characteristics of the cements for specific periods.

In the following chapter, the second main constituent of concrete, aggregates, will be discussed and shown that a development in terms of use and quality can be observed as well.

Chapter 4

Aggregates

Chapter Outline

In the previous chapter, the development and variety of binders used for historic concrete were discussed. Aggregates are the second main constituent of concrete and influence both the strength and durability of concrete, and colour of exposed concrete. Historically, significant changes in the use of aggregates can be noticed. These changes were mainly driven by scientific insight into concrete technology. Wider application of concrete for housing led to the use of different types of aggregates. Together, these factors influence the heritage values of historic concrete, and the durability of concrete. For repairs, the identification of the used aggregates, their size, geometry and grading is required for the development of compatible repair mortars. In this chapter, the changes during time regarding fine and coarse aggregates, including different materials and geometry, and the grading of aggregates will therefore be explained.

4.1 Introduction

Aggregates are, together with the binder and water, the main constituents of concrete. According to the present-day standard NEN-EN 12620:2002+A1:2008 *Aggregates for concrete*, aggregates are defined as a “*granular material used in construction. Aggregate may be natural, manufactured or re-cycled*”. Depending on their size, aggregates are divided into two groups: fine and coarse aggregates. Both are used together to have a denser distribution of the aggregates and by this reducing the cement content. The present-day threshold for the maximum grain size for fine aggregates is 4 mm (NEN-EN 12620:2002+A1:2008), whereas historically mainly 5 mm was used (for example Minister van Oorlog, 1906, §177; Van der Schrier, 1938), sometimes even 7 mm (Bergsma & Homan van

der Heide, 1910b). Filler, which are very fine (< 0.0063 mm according to NEN-EN 12620:2002+A1:2008) inert materials added to improve some properties of modern concrete, did not play a role for historic concrete.

Fine aggregates have been traditionally used for mortars to reduce shrinkage, and to make the mortar more economic by decreasing the binder content (see for example Van der Kloes, 1908c). Some obsolete concrete terminology reflects the relationship between mortars and concrete, such as the German term for concrete *Grobmörtel* (literally “coarse mortar”, Van der Kloes, 1908c; Van der Kloes et al., 1924). The use of coarse aggregates is known from the Roman *opus caementicium* (see Figure 1.4). In Roman concrete structures, a range of aggregates can be found; in the Pantheon, for example, lightweight aggregates were used to reduce the weight of the upper part of the cupola (Lamprecht, 1987).

Although aggregates are in terms of volume the main constituent of concrete and relevant for its durability and strength, their historical use for concrete is seldom discussed. In contrast, nowadays, entire chapters are dedicated to aggregates (see for example Neville, 2008), and aggregates are investigated for their influence on the properties and durability of the concrete. Reviewing historic concrete literature shows that only the general benefits of using aggregates were outlined but not the properties of the aggregate itself. Research on the properties of aggregates was hence one of the later developments of concrete technology.

The role of aggregates and their influence on the properties of the concrete was initially poorly understood. As with mortars, coarse aggregates were seen as auxiliary materials to reduce the shrinkage of concrete and the cement content, as Portland cement was expensive. In the middle of the 19th century, first attempts were made to introduce a conscious choosing of aggregates in terms of geometry, material properties, and distribution (Reid, 1869; Scharroo, 1946). More attention to the choice of aggregates regarding geometry and size distribution would not be given until the beginning of the 20th century (see Sections 4.3.5 and 4.4).

Due to their quantity, coarse aggregates influence the strength of the concrete. An initial requirement was that their compressive strength should be the same as that of the Portland cement used. Not much variation can be seen during time regarding the advice on fine aggregates and mainly the use of sand was described. To assure a good bond between aggregates and cement, it was advised to clean aggregates from contaminations such as clay, silt and organic matter. However, in practice not always attention was given to clean the aggregates, affecting the adhesion of the cement paste with the aggregate (see Figure 4.1, Scharroo, 1916).

The requirements of the first two editions (1912, 1918) of the *Gewapend Betonvoorschriften* (G.B.V., Netherlands Code of Practice for Reinforced Concrete) were simple: a minimum and maximum size, a sufficient yet not further defined compressive strength, and no nameable contamination. In the third edition (1930), the requirements were identical, yet for the first time the use of standard sieves is described to determine the aggregate size, reflecting the general introduction of standards in the Netherlands. Only with the 1940 edition, the requirements

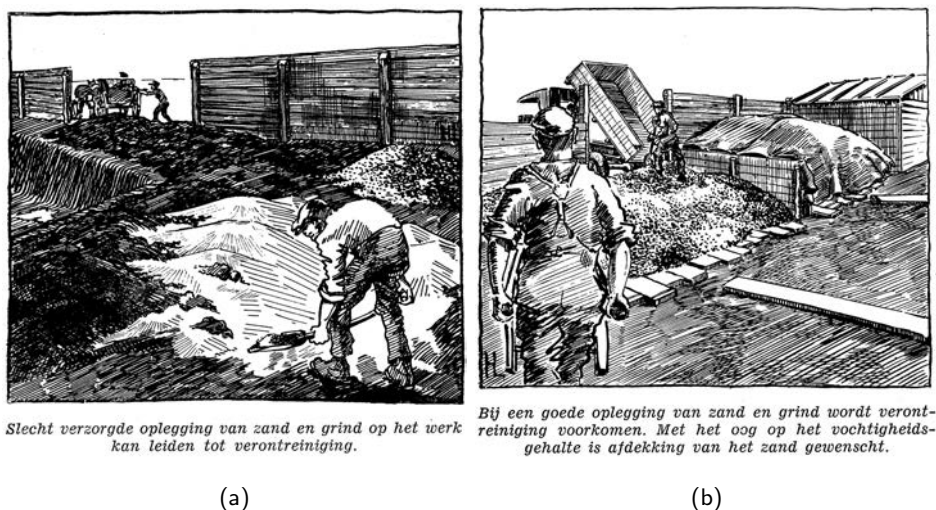


Figure 4.1 Illustrations addressing the possible sources of the contamination of aggregates. a) “Poor storage of the sand and gravel on-site can cause contamination” (Scharroo, 1929, p. 41). b) “With a good storage of sand and gravel contamination can be avoided. Considering the humidity, a covering of the sand is desirable” (Scharroo, 1929, p. 43).

became more sophisticated in terms of grading and desired concrete quality by introducing the fineness modulus (see Section 4.4). In the G.B.V. 1962, aggregates are called for the last time *grind en steenslag* (gravel and crushed rock); in the 1974 standard for reinforced concrete *Voorschriften Beton* (VB 1974), they are called *grove toeslagmaterialen* (coarse aggregates). With the VB 1974, for the first time, an own standard for sand and gravel is introduced, the NEN 3542:1973 *Zand en grind voor gewapend beton en voorgespannen beton* (Sand and gravel for reinforced and prestressed concrete). Compared to modern standards, these initial demands are limited. Today, an entire standard, the NEN-EN 12620:2002+A1:2008 *Aggregates for concrete*, is dedicated to aggregates used for concrete, regulating the geometrical, physical and chemical requirements.

The changes and differentiation of the guidelines reflect the scientific insight gained in the first decades of the 20th century. It was understood that a good concrete does not only depend on a good cement, but on the other constituents, aggregates and water as well, not only in terms of quality but also of quantity. The changing perception of the role of the aggregates and improvement of concrete technology can be seen in historic concrete, with each period with distinguishing features, varying from materials used, geometry and grading.

In the following sections the changes regarding the fine aggregates (Section 4.2), coarse aggregates (Section 4.3), and the grading of aggregates (Section 4.4) will be explained more in detail.

4.2 Fine aggregates

The most commonly used fine aggregate for concrete was and is natural sand (compare for example Neville, 2008; Van der Kloes, 1908c). The origin of the sand varied from river, dune or sea, and sand extracted from fields and heath (Van der Schrier, 1938, 1942). In the first two editions of the G.B.V. from 1912 and 1918, however, only river sand was allowed (Table 4.1). The advised rivers for dredging sand were Rhine and Meuse, sometimes Waal and Lek (Scharroo, 1910a, 1916, 1921; Van der Kloes, 1893, 1908c). In the G.B.V. 1930, the origin of the fine aggregate was not restricted anymore. In regions more remote from the main rivers, these changes supported the use of cheaper, local sands. To limit the amount of sand dredged from the main rivers, research was carried out on the suitability of other sands (Van der Schrier, 1953). The use of so-called manufactured sands, or crushed rock, made from granite or basalt, was not excluded in practice (Bergsma & Homan van der Heide, 1910b) and can be encountered for example in coloured exposed concrete (Bergsma, 1934).

Reasons for initially limiting the origin of sand were the fineness (see Figure 4.2) and contamination of other sands. It was advised against the use of too fine aggregates as they could agglomerate with each other and not with the binder, leading to a weaker concrete. In addition, smaller grains have a higher surface area, requiring more water, and plasticisers were not available yet which could reduce the water amount. For these reasons the use of dune sand and from the river group *Benedenrivieren* (e.g. Merwede, Lek, Nieuwe Maas, Hollands Diep, Bergse Maas, Nieuwe Waterweg) was not advised as they were too fine and too contaminated (Boon, 1908; Scharroo, 1910a; Van der Kloes, 1893). Besides size and degree of contamination (e.g. clay, silt and organic matter), the shape was the third criterion for selecting fine aggregates.

As the quality of the concrete was initially defined by the strength of the cement, the quality of the sand used for test samples was important (since test specimens were not always made with coarse aggregates). The use of similar sands for testing and comparing different concretes was strongly advised, as different sands could lead to different test results (Van der Kloes et al., 1924). A good Dutch sand used as a reference for tests, which was comparable to the German standard sand, was sand from the river Waal near Nijmegen (Van der Kloes, 1908c; Van der Kloes et al., 1924). An early practical concern for the testing of sands was that it was difficult to obtain good sieves (details about sieves see Section 4.4).

4.3 Coarse aggregates

Already in the 19th century, coarse aggregates for (plain) concrete structures were classified in three main groups: gravel (Section 4.3.1), crushed stone (Section 4.3.2), and broken bricks (Section 4.3.3), although crushed stone and broken bricks were sometimes seen as one category (Minister van Oorlog, 1906; Van der

Table 4.1 Maximum sizes and grading of fine aggregates in different editions of the G.B.V.

Sand type	Quality class	Sieve type ^a	Size (mm)	quantity	Fineness modulus
G.B.V. 1912	Clean, coarse river sand	n/a	< 5		n/a
G.B.V. 1918	Clean, coarse river sand	n/a	< 5		n/a
G.B.V. 1930	Clean, coarse and sharp/angular sand	n/a	N 380 - d-5.6	max. 5%	n/a
G.B.V. 1940	Clean, coarse and sharp/angular sand	n/a	N 480 - d-5.6 N 480 - d-2.8 N 480 - d-0.300	max. 5% max. 15% min. 3% max. 15%	2.10 – 2.80
G.B.V. 1950	Clean and coarse sand	n/a	N 480 - d-5.6 N 480 - d-2.8 N 480 - d-0.300 N 480 - d-0.150	max. 5% max. 15% min. 3% max. 15% max. 10%	2.10 – 2.80
G.B.V. 1962	Clean and coarse sand	K160	N 480 - d-2.8 N 480 - d-0.300 N 480 - d-0.150 N 480 - d-0.050	max. 15% min. 70% max. 97% min. 90% min. 98%	none required
		K225 and K300	N 480 - d-2.8 N 480 - d-0.300 N 480 - d-0.150 N 480 - d-0.050	max. 15% min. 77.5% max. 92.5% min. 95% min. 98%	2.1 – 3.0

^aSieve sizes N480 resp. N 380 stands for the Dutch standard N 480:1933 *Contrôle-zeven*, d for the mesh size followed by a numerical indicator in mm.

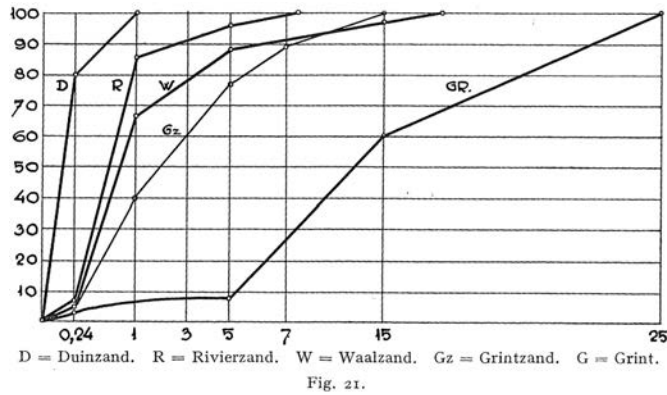


Figure 4.2 Comparison of grading curves of different Dutch sands (D= dune sand; R= river sand; W= sand from the Waal), *grindzand* (GZ) and gravel (GR). The abscissa shows the mesh size in mm, the ordinate the percentage of sand passing the mesh (Bergsma, 1934, p. 32).

Kloes, 1893, 1908c). Aggregates for special types of concrete, such as lightweight concrete (Section 4.3.4) were only addressed more commonly from the beginning of the 20th century. After outlining the historical context, the different aggregates will be discussed more detailed in the respective sections.

Early technical demands concerned the compressive strength of aggregates, which should be similar to the compressive strength of the Portland cement (Boon, 1908). More practical requirements regarded the price and availability of the aggregates. As the Netherlands depended on the import of natural stones, mainly from Belgium and Germany, crushed stone was more expensive than locally available gravel or broken brick. With the First World War and the limitations of importing natural stone, the use of gravel became even more economic. Additionally, the use of crushed stone required more cement than gravel, thus causing extra expenses. Therefore, gravel became the common coarse aggregate for normal structures. An overview of advised types and periods of use of coarse aggregates for common concrete types is given in Table 4.2.

An early example of careful optimisation by using different aggregate types balancing function and costs can be seen in the some forts of the Stelling van Amsterdam. For Fort Bezuiden Spaarndam (1897-1901) strategically important and more exposed elements were constructed with crushed rock, in this case porphyry. Construction drawings show that secondary elements and interior elements, such as foundations and internal walls were designed with gravel or broken bricks (see Figure 4.3).

The type of rock used as aggregate was in general a secondary concern, except for exposed concrete where the aesthetic qualities of different natural stones (colour, geometry) were of importance (see Chapter 7 *The surface finish of historic concrete*). For exposed concrete, a wider variation of aggregates can be

Table 4.2 Overview of coarse aggregates advised in historic Dutch concrete textbooks.

	Natural aggregates										Artificial aggregates	Lightweight aggregates			
	Gravel				Crushed stone										
	River gravel	Pit Gravel	Sea Gravel	Grindzand	Basalt	Granite	Porphyry	Quartz	hard rocks (generic)	Gneiss					
until ca. 1920s	✓✓	✓			✓						✓✓				
	○	○			○	○	○	○	○	○	○				○
	○	○			○	○	○	○	○	○	○				○
	○	○			○	○	○	○	○	○	○				
	✓✓	✓✓		✓	✓	✓			—		—				—
	✓✓	✓✓			✓✓	✓✓			—	✓✓	—/○				
	Heide (1910b)														
	Scharroo (1910a,b)	✓✓	✓✓	✓		○/—	○/—	○/—	○/—	○/—					
ca. 1920s-1940s	Van der Kloes, Jacobs, Tjaden & Wentholt (1923); Van der Kloes et al. (1924)	✓ ¹	○/—		✓	✓		✓							
	Boon (1931)	✓✓	✓✓		○/—										✓
	Bergsma (1934)	✓✓ ²	○		○										
	Van der Schrier (1938, 1942)	✓✓ ²	✓		✓	○/—	○/—				○/—	○/—	○/—	○/—	✓
	Zwolsman (1940)	✓ ²	✓		✓	✓	✓	✓	✓			✓	✓	✓	✓
	Scharroo (1940, 1942a)	○	○	○/—			○/—				○/—	○/—	○/—	○/—	○/—
	Van der Schrier (1949)	✓✓ ²	✓			○/—	○/—				○/—	○/—	○/—	○/—	
	Van Dijk & Van der Baan (1952)	○ ²	○			○	○	○	○						○
ca. 1940s-1960s	Van der Schrier (1957)	○ ²	○/—			○	○	○	○			○/—	○/—	○/—	○/—
	Bond van Fabrikanten van Betonwaren in Nederland (1957)	○	○			○	○	○	○						
	Van der Schrier (1960)	✓✓ ²	○/—			✓	○/—		○/—		○/—	○/—	○/—	○/—	○/—
	Van der Schrier (1968)	✓✓ ²	○/—			✓	✓	✓	✓		○/—	○/—	○/—	○/—	○/—

Legend: ✓✓ main advice or mainly used aggregate; ✓ advised; ○ neutral; ○/— limited, seldom used; — unadvised.

1) Specifies *Meuse*, *Rhine* and *Waal* types of *River gravel*; 2) Specifies *Meuse* and *Rhine* types of *River gravel*.



(a)

Fig. 12. Doorsnede volgens K.S. op fig. 1. (1:100).

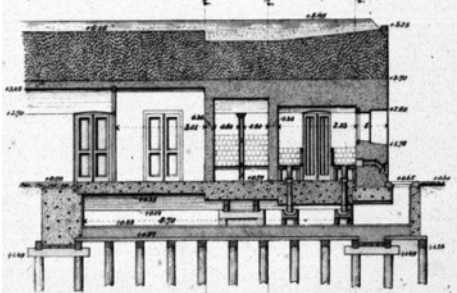
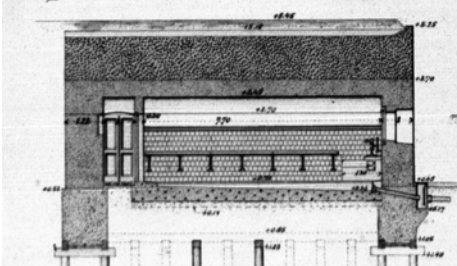


Fig. 8. Doorsnede volgens J.K. op fig. 1. (1:100).



(b)

Aanwijzing.

			Koud	Land	Stem
Cementbeton van grind			3	2	4
Idem	id.		3	3½	3
Idem	id.		3	2½	5
Idem van porfier			3	5½	4½
Idem	id.		3	2	4
Idem	id.		5	3½	3
Idem	id.		3	5	3
Idem van klinklapuin			3	2½	4½

(c)

Figure 4.3 Example of a plain concrete building with an optimised use of coarse aggregates (Fort Bezuiden Spaarndam, part of the Stelling van Amsterdam, 1897-1901). a) Overview, as the surface is covered with a thin render, variations in the aggregate use cannot be seen. b) Detail drawings of two sections, showing the use of different concrete mixes (3de bald, 23. October 1900). For elements more exposed to impact of shells such as the roof, a different mix (probably with porphyry) was used than interior walls or ground slab. c) Legend of the construction drawings. From top to bottom: concrete with gravel with three different concrete mixes; concrete with porphyry, with four different concrete mixes, and one mix using broken bricks (see also Table 5.3).

encountered, not only natural stones and broken bricks, but also broken glasses and mirrors, as can be seen for example in the post-World War II works of Hermanus Gerardus Jacob Schelling (1888-1978). In the 1920s, with the increased use of concrete for housing with higher demands towards sound and heat insulation, lightweight aggregates such as pumice and municipal solid waste incineration bottom ash became more common (see Section 4.3.4). An exploration of possible aggregates can also be noticed in periods of scarce materials, such as during and after the Second World War. Besides the recycling of broken bricks from debris, slags were alternatives for gravel and stone (Wendehorst, 1949).

In the G.B.V., the useable types of minerals as aggregates for reinforced concrete were not addressed. Only general reference to *grind* (gravel) and *steenslag* (crushed stone) was made. The NEN 3542:1973 *Zand en grind voor gewapend beton en voorgespannen beton* (Sand and gravel for reinforced and pre-stressed concrete) reduced the used coarse aggregate types to gravel, and the use of quartz assumed (Smit, 1974).

Similar to cements, the naming of the concrete was influenced by the used aggregate. The Dutch obsolete terms *Portlandcementgrindbeton* ("Portland cement gravel concrete") and *cementgrindbeton* ("cement gravel concrete") refer to concrete with gravel; when gravel became the common aggregate, a concrete without any further definition usually implied its use. If special, thus not the common gravel, aggregates were used, the naming of the concrete could indicate the aggregate type: *brikkenbeton* (concrete with broken bricks) *steenslagbeton* (concrete with crushed rock), *puimsteenbeton* (concrete with pumice), *slakkenbeton* (concrete with breeze/cinder, not to be confused with *slakkencement*), *sintelbeton* (concrete with municipal solid waste incineration (MSWI) bottom ash), *korrelbeton* (a Dutch patent for a concrete made with slag) (Boon, 1920; Scharroo, 1925).

The criteria for aggregates became more detailed and complex during time. Initially, the maximum size and the purity of the aggregates were the main concerns. Since the Interwar period, a more differentiated evaluation was discussed, including geometrical, physical and chemical requirements similar to those of the present day standard NEN-EN 12620:2002+A1:2008. Evaluated were the geometry of aggregates (size, shape, surface texture), packing (bulk density, specific weight), density (incl. grading), chemical composition (incl. contamination) and strength and physical properties (e.g. porosity, freeze-thaw resistance, fire resistance, compressive strength) (Burchartz et al., 1927). After the Second World War, the durability of the aggregates is addressed more often, and adequate testing of aggregates suggested (Van der Schrier, 1960, 1968).

As in some cases damage symptoms appear only after decades, the understanding of a possible relationship between aggregates and unexplainable damage symptoms took time. For example, it was not until 1940 in California, United States of America, that a relationship between used aggregates, cement type, and the appearance of specific crack patterns was identified, the so-called alkali-aggregate-reaction (AAR) or alkali-silica-reaction (ASR, see Figure 4.4, Bogue, 1947; Bosschart, 1957; Stark & Wicht, 2001). Initially, it was thought that the

risk of ASR was low in the Netherlands, as the local available aggregates were considered non-reactive (van de Fliert, 1962). Further research was required to determine which aggregates are reactive. Only in 1994, the CUR Recommendation 38 concerning ASR and aggregates appeared in the Netherlands (CUR report 1994a; Nijland & Siemes, 2002). ASR has been identified for example at several concrete sluices dating from the 1930s (Swinkels & Boutz, 2003).

4.3.1 Gravel (*Grind*)

Already at the beginning of the 20th century, gravel was the most commonly coarse aggregate used in the Netherlands (Boon, 1908). It was locally available, and thus (its use) economical. Its use for reinforced concrete was never excluded (see for example Figure 4.5 and Figure 4.6), and together with crushed stone mentioned in the first G.B.V. from 1912. For military structures the use of river and pit gravel was allowed as well (Minister van Oorlog, 1906, §89).

Gravel was initially not the preferred aggregate regarding the quality of the concrete. The main considered disadvantage was that it had less surface area than crushed stone, reducing the bond between aggregate and mortar. An advantage then not considered was that the use of gravel requires less water and thereby reduces the risk of segregation and bleeding. Yet, gravel became widely appreciated as it was cheaper and easily (locally) available. Also, as gravel is round, it requires less cement than angular crushed stone. The different particle sizes in a gravel mix supported the use of less cement as well, as voids were filled with the smaller particles of the gravel and not with cement (Bergsma & Homan van der Heide, 1910b; Boon, 1908).

The types of gravel were categorised after their excavation location: river gravel, pit gravel and sea gravel. A fourth category was based on a natural pre-mix grading usable for concrete, the so-called *grindzand*, a natural all-in gravel. In general, the types of minerals was not further defined, besides occasionally mentioning siliceous aggregates (for example Bergsma & Homan van der Heide, 1910b).

River gravel (*rivier grind*) was mainly dredged from the rivers Rhine and Meuse, periodically also from the Waal. The winning of gravel from the Waal was forbidden in 1913, as it interfered too much with the shipping, but in the 1920s it was partially allowed again (Van der Kloes et al., 1923). Attention had to be paid that the gravel was not contaminated with coal and ash from shipping (Betonvereniging, 1929). The properties of the different gravels were described as following: gravel from the river Waal consists mainly of yellow and white quartz stone, Meuse gravel of quartz, sandstone, and is yellowish-brown; Rhine gravel is flatter than Meuse gravel (Scharroo, 1942b, 1944; Van der Schrier, 1949).

Pit gravel (*berggrind*) was initially mainly used in the east of the Netherlands, and its use was regionally restricted, as transport costs made the use of river gravel more economic in other regions. Initially, pit gravel was considered to be superior to river gravel, as it had a rougher surface (Bergsma & Homan van der Heide,

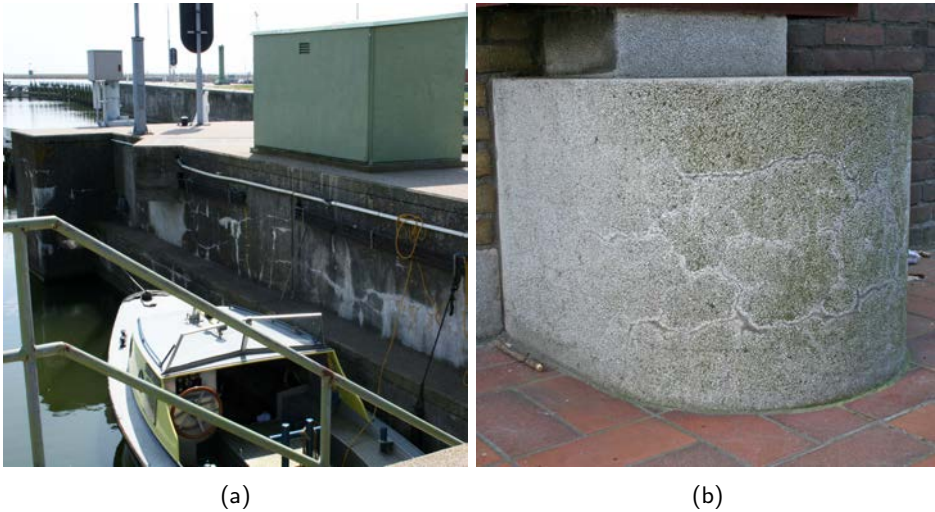


Figure 4.4 Two examples of ASR encountered in historic concrete dating from the 1930s, showing a typical ASR crack pattern. a) Lorentz sluice (Kornwerderzand 1932, situation 2009). b) Decorative concrete element (social housing, Rotterdam, 1935, M. J. Granpré Molière and P. Verhagen, situation 2010).



Figure 4.5 Early example of reinforced concrete made with gravel; notice that between the reinforcement bars only smaller sized aggregates are present (circumambulation passageway, Pilgrimage church, Brielle, 1912, situation 2010).



Figure 4.6 Example of use of gravel for exposed concrete; the gravels are locally visible due to segregation of the concrete during construction (Pumping station Parksluizen, Rotterdam, G. J. van der Grinten, 1967, situation 2008).

1910b) but not allowed in the G.B.V. 1912. Its higher degree of contamination with clay and associated cleaning costs, led to giving river gravel the preference (Probst, 1917; Van der Kloes et al., 1923).

For fortifications, the use of **sea gravel** (*zeegrind*) is mentioned in the first half of the 20th century by the military engineer Scharroo. Sea gravel mainly consists of siliceous aggregate and chert. The deleterious effect of a possible too high salt contamination, however, was always mentioned (Scharroo, 1916, 1921, 1940, 1942a, 1944). The use of marine aggregates was not common and only reintroduced in the last decades of the 20th century (see for example Nijland & Siemes, 2002).

Grindzand (Natural all-in gravel, *Arnhemsch zand*) is a natural pre-mix of coarse and fine aggregates (see also Figure 4.2), usually of finer gravel and sand with a grading of 0 – 20 mm (Bergsma, 1934; Van der Kloes, 1908c; Van der Kloes et al., 1923; Zwolsman, 1940). Its use was mainly advised between 1910 and 1930; a period before design rules for grading of the aggregate were applied (see Section 4.4). Van der Kloes et al. (1924), whose later advices are sometimes conservative, still advised to use *grindzand* in the 1920s instead of normal sand, due to the mixture of different grain sizes. Boon (1908, 1913, 1920) initially considered it as an excellent material for a low-cost concrete and states that it was often used. In the fourth edition (1931), however, *grindzand* was considered less suitable as its grading was not constant, leading to a concrete with non-uniform properties. Bergsma (1934), occasionally conservative as well, was still positive about *grindzand*, and criticised more its high price and difficulty to obtain. The change of mind in the 1920s and 1930s reflects new scientific insight and the changing perception on the importance of a good concrete mix, which included a designed grading of the aggregates (see Section 4.4).

4.3.2 Crushed stone (*Steenslag*)

Crushed stones are either mechanically crushed natural stones or quarry refuse. They can be distinguished by their sharp edges and more angular shape. Their use declined in the first decades of the 20th century.

Crushed stone, despite its higher price, was initially considered to be superior to gravel as its rough surface offered more surface area to bond with the cement (Van der Kloes, 1893). Additionally, the freshly broken surface was less contaminated. Crushed stone and broken bricks were commonly advised for plain concrete (Becker, 1857; Storm van 's Gravenzande, 1850, 1863).

Beside possessing sufficient strength, which was defined as the same strength as that of the cement, the used natural stones should not be brittle, non-eroding and not absorb water (Minister van Oorlog, 1906; Probst, 1917; Van der Schrier, 1938, 1942). The main advised natural stones were basalt, granite, porphyry (see Table 4.2). Porphyry from the Halle area South of Brussels was specifically indicated as porphyry from Quenast and very popular; even an own terminology was applied for the different sized stones (Christophe, 1905; Van der Kloes et al., 1923). It was used for the early plain concrete forts of the Stelling van Amsterdam,

as these were important buildings which required a strong concrete (Figure 4.7). Some natural stones were explicitly not advised such as sandstone, trachyte and lava (Bergsma & Homan van der Heide, 1910b; Boon, 1908; Probst, 1917). For exposed concrete, a wider variety of natural stones can be found (see Chapter 7 *The surface finish of historic concrete*) and commonly encountered in the Interwar period (Figure 4.8).

4.3.3 Broken bricks (*Puin/brikken*)

Broken bricks (*brikken*¹) are a manufactured aggregate. As the Netherlands did not have many natural resources for natural stone, but a strong tradition in brick production, early plain concrete structures were often made with broken bricks. An obsolete Dutch term used in the late 19th century for (plain) concrete made with broken bricks is *brikkenbeton*. In documents dating from the early and middle 19th century *beton* (concrete) could refer to a concrete made with broken bricks as they were rather commonly used as coarse aggregate before the introduction of reinforced concrete (see also Heinemann et al., 2012). The use of broken bricks was mentioned in foreign literature as well (for example Becker, 1857; Reid, 1879).

Broken bricks were strongly advised for large plain concrete structures in the late 19th century (Storm van 's Gravenzande, 1850, 1863; Van der Kloes, 1893). Several Dutch military defence lines are known for their use of *brikkenbeton*: the *Nieuwe Hollandse Waterlinie* (from 1816 onwards, see Figure 4.9), the Stelling van Amsterdam (1880-1920, now a UNESCO World Heritage Site) with the forts near Abcoude (1887), Pampus (1895) and near IJmuiden (1888) (Gaasbeek, 2003), the sea defence Hellevoetsluis (17th century, with major extension 19th century, Figures 1.4 and Figure 4.10) or the fortified garrison town Naarden (e.g. elements of bastion Katten, 1878, 1895). Civil examples for plain concrete made with broken brick and lime can be found in the sluices of the Zuidwillemsvaart canal (1824-1825), the foundations of the St.-Andries sluice and the steam pumping station Bommerlerwaard (1854-1855), a quay-wall in the harbour of Rotterdam (1874), and for bridge foundations throughout the 19th century (Storm van 's Gravenzande, 1850, 1863; Van Bergen, 1959; Van der Kloes, 1893) and for foundations of hydraulic structures as in the pumping station Vier Noorder Koggen in 1868.

The bricks used could be either new or debris. For military structures the use of debris from torn down walls or streets was allowed, but not roof tiles, lime rubble, or garbage (Minister van Oorlog, 1906, §88). When using debris the risk of contamination with soluble salts had to be considered (Probst, 1935). Normal bricks and clinker bricks could be used. Later, warnings were given of not to use normal brick as it is more prone to freeze-thaw damage, instead clinkers bricks were advised (Bergsma & Homan van der Heide, 1910b). As broken bricks were mainly used for plain concrete structures they are neither often mentioned in reinforced

¹The origin of the Dutch word *brik* is not clear; some associations are to the French *brique* or English *brick* (e.g. Van der Kloes, 1893, p. 387); other explanations are that the word origins from the Dutch *breken* and was used for broken or misfired bricks.

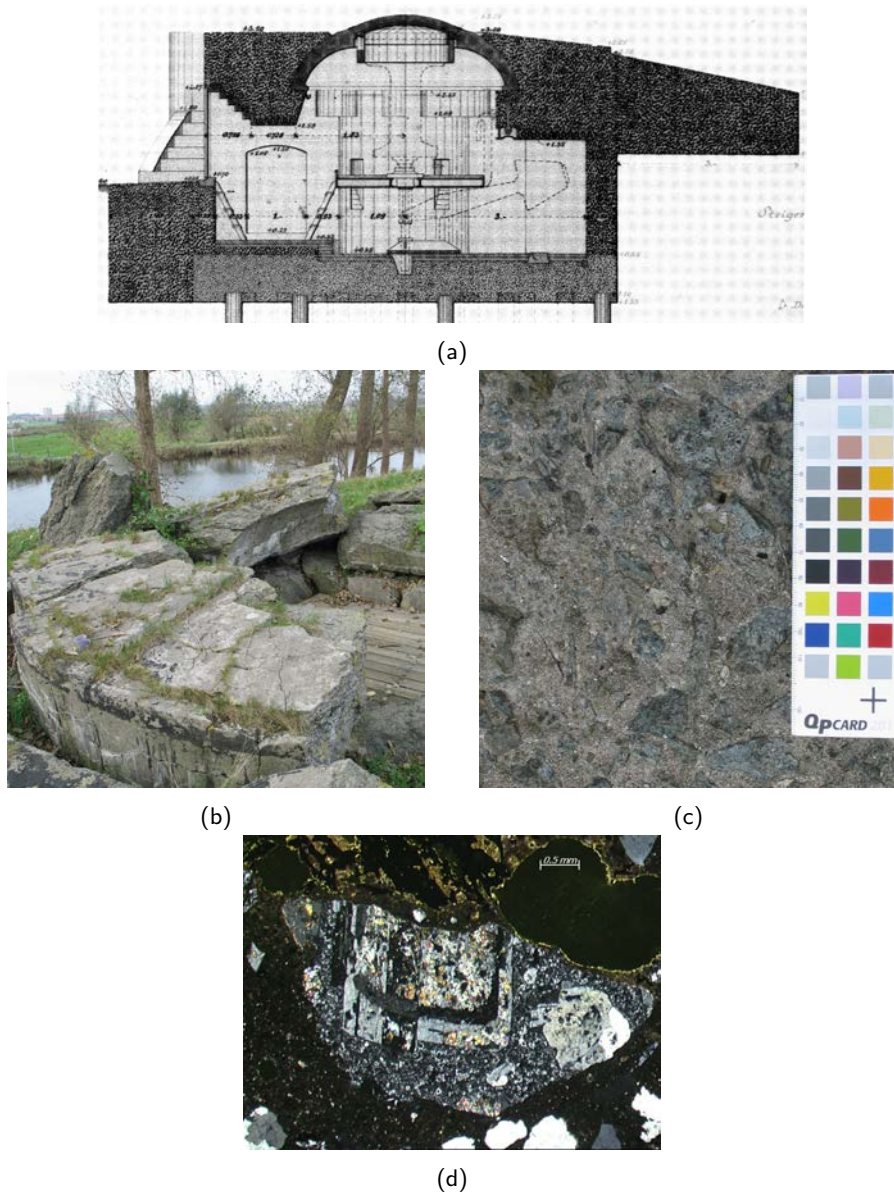


Figure 4.7 Example of different references and methods to indicate the use of crushed stone as aggregate (gun turret of Fort Bezuiden Spaarndam, 1897-1901, situation 2006). a) Original construction drawing of a section of the gun turret indicating the use of different concrete mixes (Legend see Figure 4.3; 3de bald, 23. October 1900). b) Overview, the gun turret was blown up by the German occupation Army in the Second World War (situation 2006). c) Fractured surface of the gun turret, exposing porphyry as coarse aggregate (situation 2006). d) Photomicrograph of thin section from the gun turret identifying porphyry as aggregate, most likely from Quenast (25 x, Cross polarised light, picture Timo G. Nijland).



(a)



(b)



(c)

Figure 4.8 Combined use of natural stone and concrete with crushed stone; both surfaces have been bush hammered to increase a similar appearance (housing Rotterdam, Walenburgerweg, architect and exact date unknown ca. 1933, situation 2011). a) Overview. b) For the concrete soffit a green stone as aggregate was used, possibly the same as for stairs. c) For the stairs natural stone, Anröchter Grünstein, a German limestone, was used.



Figure 4.9 Example of plain concrete from the Nieuwe Hollands Waterlinie, ca. 1850 made with broken bricks and a trass-lime binder. The angular shape of the aggregates in combination with manual compaction explains the presence of voids near the aggregates. No contaminations were found along the edges of the aggregate, indicating the use of new bricks and not debris (see also Heinemann et al., 2012) .

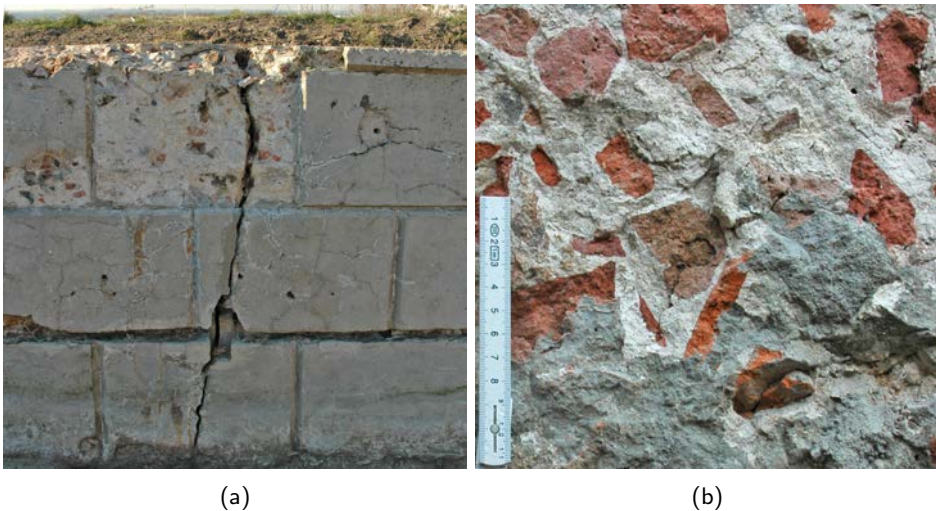


Figure 4.10 Example of plain concrete made with broken bricks in a military structure (Fortification Hellevoetsluis, built from 1880 onwards; situation 2012, pictures Wido Quist). a) Detail of wall with locally missing render, exposing the plain concrete. Clearly visible are the imitated joints in the render. b) Detail showing use of broken bricks and traces of a darker render; the colour differences indicates the use of Portland cement for the render, and a lime based binder for the concrete.

concrete textbooks, nor discussed in the G.B.V. A limitation of the aggregate size was less relevant, as broken bricks were mainly used for plain concrete. A common size was between 2 – 6 cm (Scharroo, 1942b).

In the Interwar period, broken bricks were only advised for secondary uses such as backfill concrete (Van der Schrier, 1938, 1942). In the reconstruction period after the Second World War and the following material scarcity, attention was given again to the use of broken bricks (Wendehorst, 1949). However, such a use in the Netherlands is hardly documented but memories exist that broken bricks were used for housing in The Hague or other regions, which suffered severe damage during the war.

Already in the 19th century, broken bricks were used for decorative concrete elements to reduce the cement content (Stokroos, 1985). Other areas of application of broken bricks and glazed stoneware were for decorative concrete and are described in Chapter 7 *The surface finish of historic concrete*. The possibilities of large-scale use of recycled aggregates such as broken bricks for concrete was only scientifically investigated in the 1980s (see for example Hendriks, 1983).

4.3.4 Aggregates for lightweight concrete

The building physical properties of concrete are for some uses often unsatisfactory; especially its poor sound and heat insulation was an early concern. By choosing lighter aggregates these properties could be improved. Another side effect was that the dead load was reduced. The use of lightweight aggregates was mainly restricted to concrete fills, concrete blocks or plain concrete, seldom for reinforced concrete as it offered little protection against corrosion.

At the end of the 19th century, lightweight concrete was used as fill for arches (Bergsma & Homan van der Heide, 1910b), as insulation layer on top of concrete roofs (Scharroo, 1916) and for partition walls (Probst, 1935; Van der Kloes, 1908c; Van der Schrier, 1938). Its application became more common in the 1920s with the increase use of concrete for housing with higher demands towards sound and heat insulation. Additionally, these aggregates made the concrete soft enough to hammer nails, an important aspect in the period prior to the development of the electric (hammer) drill. Its low strength, however, limited its structural use (Burchartz et al., 1927; Christophe, 1905; Van der Schrier, 1938, 1942; van Rossum, 1902).

Different types of lightweight aggregates were used. Pumice (*bims*) was commonly advised and the produced concrete called in Dutch *bimsbeton* (pumice concrete, Bergsma & Homan van der Heide, 1910b; Probst, 1935; Scharroo, 1916; Van der Kloes, 1908c; Van der Schrier, 1938, 1942). Another common group of lightweight aggregates were made from waste products. Attention is however necessary, as the terminology is not always consistent in historic documents. Especially the term *slak* (slag) was used more generically than it is now. When used for binders, *slak* usually referred to blast furnace slag, yet as aggregate *slak* could refer to both

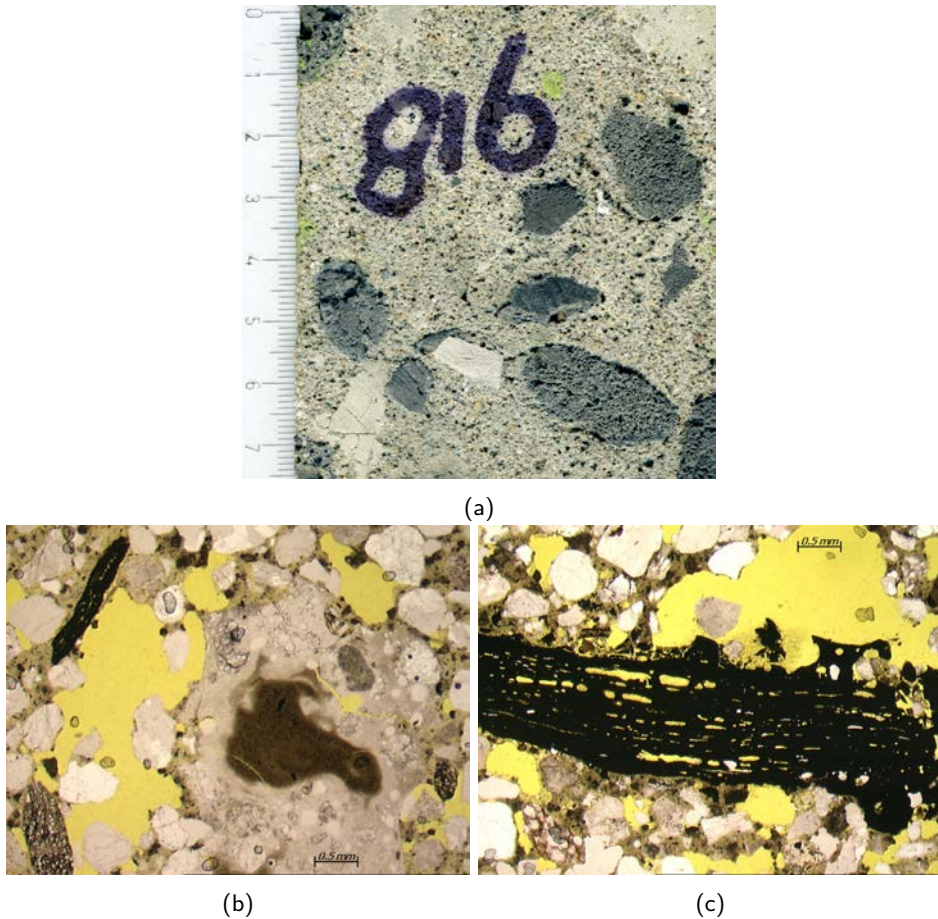


Figure 4.11 Sample of a concrete made with breeze from the Betondorp (NB The original sample was lost during the fire of the Faculty of Architecture on May, 13th, 2008. Exact origin of the sample is unknown). a) Overview of a lightweight concrete made with breeze (*sintels*). The origin of the breeze is unknown, but from the historical context it is likely to be from a waste incineration plant. b) Photomicrograph of thin section showing breeze; notice the high porosity in the sample, possible caused by poor compaction (25x, plain polarised light, Timo G. Nijland). c) Photomicrograph of thin section showing the presence of burnt coal in the concrete, possible a contamination caused by using breeze (25x, plain polarised light, Timo G. Nijland).

breeze (or cinder) or blast furnace slag. Using present day terminology, it would be comparable to municipal solid waste incineration (MSWI) bottom ash.

Concrete made with *slakken* was called *slakkenbeton* (cinder or breeze concrete); it was cheap and light, yet had a low strength (Figure 4.11). A synonym was *sintelbeton* which better indicated the use of poor quality breeze than the higher quality blast furnace slag (Van der Kloes et al., 1924). The motivation for their use was the availability as a by-product from local municipal waste incineration plants. As a waste product, their use was often confronted with prejudices. Caution had to be given to the quality of the slags, as it was feared that the sulphur content would cause corrosion of the reinforcement. Therefore, their origin had to be considered: those from waste incineration plants were usable, whereas those from gas plants not (Sweys, 1924; Van der Kloes et al., 1924). An example for a building system made with a concrete and breeze is the Isola System (Sweys, 1924).

Slak could also refer to the heavier slags from blast furnaces, which were considered of better quality. The building system Kossel used a mix of granulated blast furnace slags and breeze (Sweys, 1924). A Dutch patent for slag bearing concrete is *korrelbeton* (see Figure 4.12 and Figure 4.13), which contained blast furnace slag as aggregate, sometimes pumice (Scharroo, 1946; Van der Kloes et al., 1924). Scharroo (1942b, 1944) mentioned the use of blast furnace slag and bottom ash for *sintelbeton*.

A wide variety of different lightweight concrete can be found in many housing projects dating from the 1920s, with the *Betondorp* (Figures 4.11 and 4.14) in Amsterdam as the most known (Kuipers, 1987). Similar housing projects were carried out in Scheveningen (Figure 4.13) and Rotterdam. The buildings were either constructed with cast concrete, concrete bricks, or prefabricated concrete elements; the concrete used was usually not reinforced. Many of the concretes were sold under proprietary names such as Isola, Kossel or Greve (Sweys, 1924).

Experiments with new aggregate types to improve the building physical properties continued after the Second World War. A new concrete type was vermiculite concrete; vermiculite is a mineral and was an interesting building material as it is heat and sound insulating, and lightweight (Hamer, 1951a,b). An early example is found in the railway station in Enschede (Figure 4.15), where Schelling used vermiculite concrete for the soffit panels to improve acoustics (Schelling, 1950b).

4.3.5 Geometry of coarse aggregate

Besides the type, the geometry became increasingly important when choosing coarse aggregates. The three main geometrical aspects which were early on discussed were the maximum size, surface texture and shape.

Concerning the **aggregate size**, mainly practical rules-of-thumb were applied prior to the existence of codes of practice. For plain concrete, which was often used for mass concrete, large aggregates were preferred to save cement and to reduce shrinkage. Advices for a maximum aggregate size used for plain concrete were

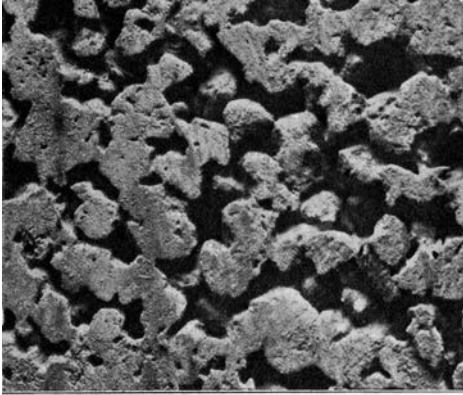


Fig. 124. Doorgezaagde muur van puimsteen-korrelbeton. 1 : 1.

Figure 4.12 Section of a *korrelbeton* made with pumice (Van der Kloes et al., 1924, p. 270).



Figure 4.13 Housing made with poured *korrelbeton* using the Greve system (see also Kuipers, 1987). The present appearance (windows, roof, colours) differs from the original (Scheveningen, W. Greve, 1920-1922, situation 2006).



Figure 4.14 Public library building built with *korrelbeton* (Betondorp, Amsterdam, D. Greiner, 1926-1928, situation 2008).



Figure 4.15 Soffit panels made with vermiculite concrete, darker claustra are made with gravel (Railway station Enschede, H.G.J. Schelling, 1950, situation 2009).

40 – 60 mm (Becker, 1857; Minister van Oorlog, 1906), not bigger than “*a child’s fist*”, respectively 50 – 70 mm (Burchartz et al., 1927; Memmler et al., 1907). Van der Kloes (1893, 1908c) defined the ideal aggregate size as “*not bigger than a chicken egg, not smaller than a pigeon egg*”²; where Bergsma was more precise in his advice by defining the size of a chicken egg with 50 – 60 mm (Bergsma & Homan van der Heide, 1910b). Probst (1935) mentioned the use of aggregates of 100 – 150 mm for mass concrete.

With the increased use of reinforced concrete, stricter size limits were required. Too large aggregates could not pass unhindered between the reinforcement and the formwork, and the individual reinforcement bars. Another practical limit was the size of the concrete element, with slender structures requiring smaller aggregates (Betonvereniging, 1929; Boon, 1908; Christophe, 1905; Van der Schrier, 1938).

Initially, the size could vary with the construction company and the chosen reinforcement type. Monier constructions were supposed to be carried out using relatively small aggregates as the reinforcement bars were placed like a mesh with only 5 – 10 cm distance; Hennebique and Melan systems, which were often used for large concrete structures such as bridges, allowed bigger aggregates yet in practice the size of the coarse aggregates was 5 – 25 mm (Christophe, 1905; van Rossum, 1902). System independent advices for reinforced concrete were “walnut sized”, or about 20 mm (Burchartz et al., 1927; Memmler et al., 1907).

Other recommendations were to differentiate between the varying loads in a concrete member, and to place larger aggregates in the compressive zone, and limit the aggregate size in the tensile zone to 6 – 12 mm (Bergsma & Homan van der Heide, 1910b). The Dutch military advised to vary the aggregate size depending on the used binder. For plain concrete made with lime-based mortars (again the obsolete concept of concrete as a mortar mixed with coarse aggregates) such as *traskalkmortel* (trass-lime mortar) and *cementkalkmortel* (Portland cement-lime mortar) the coarse aggregates should be 20 – 60 mm. When using only Portland cement, the coarse aggregate should be 20 – 40 mm in size (Minister van Oorlog, 1906). In general, the maximum aggregate size was considered to be 20 – 30 mm (Boon, 1908). An example is the Hofplein railway viaduct in Rotterdam (1900-1908, Figure 4.16), where a coarse aggregate size of 5 – 25 mm was chosen (Van Hemert, 1901).

With the introduction of the G.B.V. in 1912, the minimum and maximum sizes for aggregates were regulated. In the following editions, these values were modified. The required minimum size varied between 4.8 and 5.6 mm, the maximum size showed larger changes during time from 60 – 38 mm (see Table 4.3). The maximum size of 60 mm required in the G.B.V. 1912 and 1918 was rather high. Considering that the minimum thickness of the concrete cover was only 10 mm (Section 6.5 *Concrete cover of the reinforcement*), indicates difficulties during

² “*Het voorschrift omtrent de grootte der stukken luidt hier te land, zoowel als in het buitenland, gewoonlijk, dat deze niet groter dan een hoenderei en niet kleiner dan een duivenei mogen zijn.*” (Van der Kloes, 1893).



Figure 4.16 Gravel used for columns at the Hofplein railway viaduct; originally intended were 5 and 25 mm large aggregates, yet local deviations can be encountered. The pink discolouration of the aggregates was caused by a fire during the bombardment of Rotterdam in May, 1940. (Rotterdam, A. C. C. G. van Hemert, 1900-1908, situation 2009).



Figure 4.17 Local deviation of maximum aggregate size, the maximum size should have been 60 mm (earth retaining walls of the unfinished Groot Museum Kröller - Müller, national park Hoge Veluwe, H. van de Velde, 1921-1922, situation 2008).

construction, such as to achieve a good concrete without voids. In the third edition, the maximum aggregate size was significantly reduced to 36 mm, and again slightly increased to 46 mm in the following editions. From the 1940 edition on, a fineness modulus (a specific grading of the aggregate, see Section 4.4) is required.

In practice, the limits for the maximum size of aggregates was not always utilised, and in the 1960s, a commonly used maximum size for gravel, then the main aggregate type, was 20 – 23 mm. Additionally, it was advised to limit the diameter of the aggregate depending on the thickness of the concrete cover (CUR report 36, 1966). Depending on the quality control and selection of raw material, local deviations were not excluded (Figure 4.17).

The **shape** and the **texture** of the aggregate were not discussed in the G.B.V. Both, rounded gravel and angular crushed stone were allowed, and no preference was expressed. In textbooks, however, the advantages and limits of the two different shapes were discussed. Initially, the rough surface and angular shape of crushed stone was considered to be superior to rounded gravel. Crushed rock had a higher surface area, and thus offering more area for the cement paste for adhesion. If gravel had to be used, it was advised to use more cement to compensate the poorer adhesion (Van der Kloes, 1893). Discussion arose on which shape was superior, and the workability of the concrete became another argument. Roun-

Table 4.3 Maximum size for coarse aggregates in the different editions of the G.B.V.

	Aggregate type	Quality class	Minimum size (mm)	Maximum size (mm)	Fineness modulus
G.B.V. 1912	Gravel and crushed stone	n/a	5	60	n/a
G.B.V. 1918	Gravel and crushed stone	n/a	5	60	n/a
G.B.V. 1930	Gravel and crushed stone	n/a	4.8	< 38	n/a
G.B.V. 1940	Gravel and crushed stone	n/a	5.6	< 46	6.30 – 7.00
G.B.V. 1950	Gravel and crushed stone	n/a	5.6	< 46	6.30 – 7.00
G.B.V. 1962	Gravel and crushed stone	K160 K225,K300	5.6	< 46	none required 6.3 – 7.1

ded aggregates, such as gravel, were easier to mix and to compact (Boon, 1908; Memmler et al., 1907; Scharroo, 1910a, 1916). The use of crushed stone required a higher water content to achieve a good workability, yet a higher water content could decrease the quality of the concrete (see Section 5.3 *Mixing water*). Scientific research supported a choice based on economic aspects as the quality differences between concretes made either with gravel or with crushed stone was little (Taylor & Thompson, 1905). Duff A. Abrams (1880-1965) investigated this question as well and his findings were that the aggregate shape had less influence on the concrete strength than assumed by other researchers (Abrams, 1919). Probst (1935) carried out similar experiments and came to the conclusion that the use of crushed aggregates instead of gravel required a much higher water/cement ratio and causes a significant loss of strength.

4.4 Grading of aggregates

Besides the size and type of the individual aggregate, the grading of fine and coarse aggregates influences quality and cost of the concrete. By designing the grading of the aggregate, the strength, density, and workability of the concrete can be controlled, while reducing the cement content. The underlying concept is to distribute the different aggregate sizes in a way that the voids between the larger aggregates are filled with smaller aggregates. The two main theories for achieving the best grading are to either chose only some fractions of coarse and fine aggregates, or to use all sizes continuously (Figure 4.18). The present day terminology for these two types of grading was introduced in the 1940s, with gap-grading referring to a discontinuous grading and continuous grading to the presence of all fractions (CUR report 1, 1955). Although grading was discussed amongst academics in the 19th century, it was common practice at the beginning of the 20th century to define the mix of a concrete on an arbitrary selection of



Figure 4.18 Popular illustration of the concept of continuous grading with all fractions present (top) and gap grading where some fractions are missing (bottom) (Anon., 1968, p. 13).

aggregates and based only on proportions such as 1 : 2 : 4, without “reference to the size or grading of the fine and coarse aggregate” (Abrams, 1919, p. 1).

The French engineer R. Féret was one of the first studying the grading of aggregates in 1890-1895. His conclusions were to use only coarse and fine aggregates without intermediate sizes to achieve a strong concrete, similar to present-day gap-grading. His findings reflect the 19th century understanding of concrete as a mix of mortar with coarse aggregates, and the then common practice of using only large coarse aggregates.

At the beginning of the 20th century, S. E. Thompson and W. B. Fuller came to the conclusion that a continuous grading is the best option to obtain a strong and watertight concrete. Their advice was to use artificially graded aggregates, and to achieve the highest strength, aggregates as large as possible should be used. The aggregates should be mixed according to a curve, known as Fuller’s curve (see Figure 4.19, and CUR report 1, 1955; Taylor & Thompson, 1905).

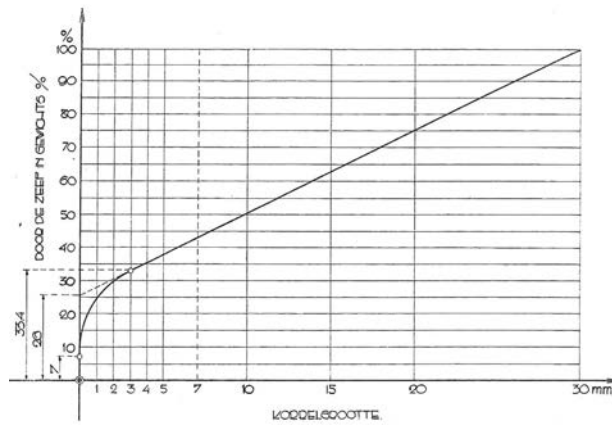


Fig. 2

Figure 4.19 Example of the aggregate size distribution according to the Fuller curve with the abscissa showing the gravel size in mm, the ordinate showing the percentage in weight of the aggregates passing the mesh (Boon, 1931, p. 26).

However, experience showed that using concrete mixed according to Fuller's curve was more prone to segregation as it contained too little of the smallest fraction. Research by J. Bolomey improved Fuller's formula in such a way that more fine material was added (Zwolsman, 1940). O. Graf followed a different theory, assuming that only the fine aggregates and the cement are the main factors influencing the strength of the concrete, and researched the grading of the smaller particles of sand and cement (Burchartz et al., 1927).

The greatest impact on the grading of the aggregates and concrete mix design however had D. Abrams and his research group in the late 1910s. Their developed formula allowed a more practical determination of the grading of the aggregate than it was possible with Fuller's curve. Abrams introduced a function which determined the fineness modulus (FM) of the aggregate and defined it as the "sum of percentages in the sieve analysis of the aggregate divided by 100. The sieve analysis is determined by using the following sieves from the Tyler standard series: 100, 48, 28, 14, 4, $\frac{3}{8}$ in., $\frac{3}{4}$ in. and $1\frac{1}{2}$ in." (Abrams, 1919, p. 4).

In the Netherlands, these changes can be observed in textbooks as well. Van der Kloes (1893), for example, advised first to only use single fractioned coarse aggregates in line with the theory of Féret. In the following edition (Van der Kloes, 1908c), the opposite, namely the use of *grindzand* (a natural mix of sand and small gravel) was advised as the different sizes could fill the voids better. In the last edition (Van der Kloes et al., 1924), only a general advice was given to use different aggregate sizes. In other early Dutch publications, a grading of the aggregates was recommended as well, yet without referring to methods to determine grading curve such as Fuller's curve (Boon, 1908, 1913, 1920; Scharroo, 1910a, 1916, 1921).

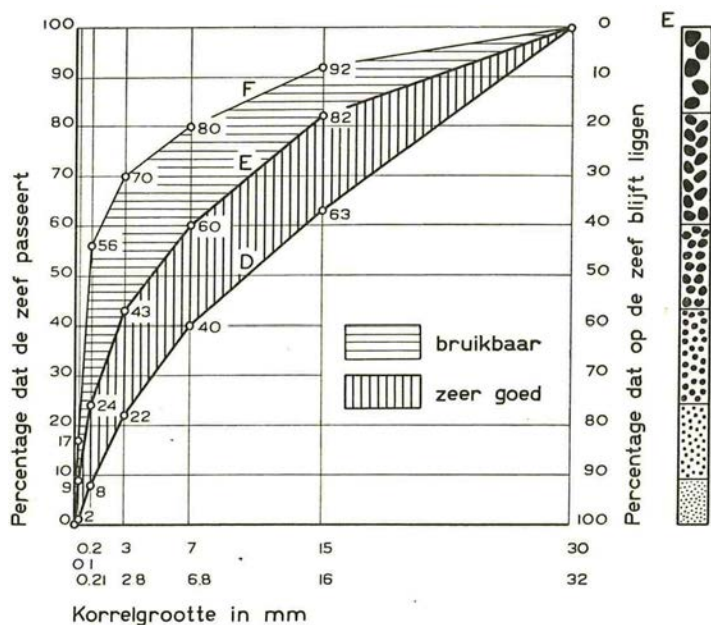


Figure 4.20 Dutch reference to grading curves used in the German reinforced concrete standard, with the abscissa showing the aggregate size in mm, and the ordinate the percentage of aggregates passing the mesh; the line *E* shows the ideal grading, *F* the maximum and *D* the minimum grading curve; aggregate distribution according to curve *E* is shown on the right (Van der Schrier, 1938, p. 33).

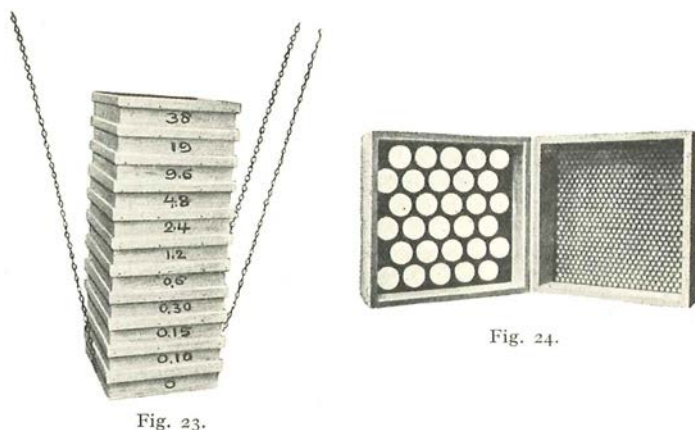


Figure 4.21 Pictures of sieves to determine the size distribution of fine and coarse aggregates: the left figure shows the stacked meshes from size 0 (bottom) to size 38. The right figure shows an opened box with two differently sized meshes (Bergsma, 1934, p. 33).

In the 1930s, the role of concrete technology and the importance of concrete mix design was discussed more frequently. The works of Abrams, Graf and Bolemey were mentioned in more detail, and the sieve analysis, use of grading curves and the calculation of fineness modulus explained. As an example for a good grading curve, reference was often made to the German standard for reinforced concrete (Figure 4.20, Bergsma, 1934; Boon, 1931; Van der Schrier, 1938).

A grading of the aggregates is first demanded in the G.B.V. 1940, were in the section on *bouwcontrole* (building inspection) fineness moduli for sand and coarse aggregates are required (see Table 4.1). The G.B.V. 1962 mentions modifications of the grading to improve the workability of the concrete while staying within the allowed water-cement factor.

A prerequisite to determinate and compare fineness moduli and the grading of the aggregates was the availability of standard sieves (Figure 4.21), which became available in the late 1920s (Probst, 1935). In the Netherlands, the use of either German, American or Dutch standard sieves was advised (Van der Schrier, 1938). Officially, sieves were only regulated with the Dutch standard N 380 in the early 1930s, which was soon renamed into N 480:1933 *Contrôle-zeven*. In this standard, which was amongst others also applied to cements, the particle sizes were determined with minimum and maximum mesh sizes, designated as d , through which they had to pass. In practice, common aggregate distribution lay between 5 and 30 mm for river gravel. The grading depended on the location of where gravel was dredged, as a modification of the natural grading was considered to be too expensive (Zwart, 1961).

In the 1930s, a deviation of the ideal curve which was based on a continuous grading was discussed again. Examples in France and Belgium and research had shown that a strong concrete was possible with “irregular” grading (Bergsma, 1934) and Dutch examples soon followed (Figure 4.22). Although in theory known for decades, a practical application was only then possible due to new and improved compaction methods and better control of the mix design. Manual compaction with poking rods or by hitting against the formwork was slowly replaced with mechanical internal vibrators from the 1930s onwards and became common in the 1950s. In this period the term gap-graded was introduced (CUR report 1, 1955; Visser, 1950). For exposed concrete, the use a gap-graded concrete was considered to be slightly better than a continuous graded as it could help to prevent blowholes (CUR report 36, 1955).

4.5 Conclusions

In this chapter it was shown that a variety of aggregates have been used for historic concrete. Their use reflects contemporary insight into concrete technology and availability of raw materials. A change was also identified in how concrete was perceived: from initially as a mortar to which rather large coarse aggregates were added, to later as a designed mix of binder, fine and coarse aggregate. Early



Figure 4.22 An early Dutch example dating from 1936 of gap-graded concrete made with blastfurnace slag cement (Sewage water reservoir, below the Jonas Daniel Meijer square, Amsterdam, picture 2008 by Timo G. Nijland).

research focussed on economic improvement by grading the aggregates to reduce voids, which would have to be filled otherwise with expensive cement, and to increase the strength of the concrete.

Deleterious effects of aggregates on the concrete took time to develop. Initial concerns regarded the contamination of the aggregates or risk of freeze-thaw damage of too porous aggregates. Other degradation effects took sometimes decades to show symptoms, with alkali-silica reaction as one of the most known damage mechanisms related to aggregates in concrete. The durability of historic concrete is not only affected by the used aggregates, but also by the grading, size and shape. When using large and angular shaped aggregates, good compaction was difficult, especially before the introduction of mechanical compaction methods in the 1930s. Lacking experience with suitable aggregate sizes and the design of the reinforcement could affect the quality as well.

The original function and construction period of the concrete structure can give first indications of the used aggregates (see also Figure 2.14 *Timeline for aggregates used for historic concrete*). 19th century defence works were commonly made with broken bricks or crushed rocks; common 20th century structures were made with gravel. For plain concrete, large aggregates were preferred, reinforced concrete required smaller aggregates. The higher building physical demands for housing led to increasing use of lightweight aggregates in the Interwar period. For exposed concrete, aesthetical demands influenced the choice as well, which will be discussed more in detail in Chapter 7.

The aggregate used can often be identified on-site. Some special surface finish techniques expose the aggregate on purpose, in other cases, the aggregates are

often visible at damaged areas. In construction drawings and specifications, the intended aggregate is sometimes mentioned, yet it has to be confirmed on-site. If not visible, a hypothesis can be made from the historical context and building typology. Conformation of the used mineral can be given with petrographic examinations. Further material research should be initiated if present damage symptoms correspond to degradation mechanisms involving aggregates (e.g. ASR) or caused by their possible contamination (e.g. secondary ettringite formation). For the development of a compatible repair concrete, the used aggregate and grading should be determined for technical and aesthetical reasons (see Chapter 9).

Chapter 5

Concrete mix design

Chapter outline

In the previous chapters, the main constituents of concrete - binders and aggregates - were discussed. The quality of the concrete depends not only on the quality of the individual constituents but also on their proportions. In this chapter, the development of rules for the concrete mix design, namely cement content and water content, will be discussed. The development is characterised by an initial emphasis on workability and cost reduction, to later growing insight into the influence of the mix design on durability and strength. In this context, admixtures and additives are addressed, as their use not only intended to improve the workability and properties, but also permitted changes in the concrete mix design.

5.1 Introduction

The quality of concrete not only depends on the quality of the individual constituents and construction methods but also on the mix design. The main variables are the binder, aggregates and water content and the grading of the aggregates (Section 4.4). Initial criteria were costs, strength and workability of the concrete, and the function and type of building element. General advice for a good concrete mix did not exist, yet a common demand was to use as little mortar as possible to save costs and reduce shrinkage. Again, the concept of concrete as mortar (binder, fine aggregates, water) to which coarse aggregates are added can be noticed in historic textbooks (for example Bergsma & Homan van der Heide, 1910b; Van der Kloes, 1893). The transition from empirical based mix design to scientifically based mix design rules took only slowly place in the first decades of the 20th century. The use of additives and admixtures to improve the desired performance of the concrete mix was not uncommon for historic concrete, yet less compared to modern

concrete mix designs. A consideration of the environmental class to which the concrete is exposed (details see Section 6.5 *Concrete cover of the reinforcement*) was not a concern of early concrete mix designs.

Initially, the mix design was empirically based using practical rules-of-thumb. A method to determine the required mortar content by measuring the voids between the coarse aggregate was described by Scharroo (1910a): a barrel full of coarse aggregates was filled with water, the water content measured and 15% as safety factor added. Scharroo (1946) reflects the early practice of concrete mix design as a period of careless mixing with the common practice to simply mix cement, sand and gravel in a more or less defined quantity and add some water. Scharroo himself (1910a) advised then the simple rule to use the double amount of coarse aggregates than fine aggregates.

The formulation of the mix design varied during time. Most common was the expression in volumes and proportions of the constituents: 1 part cement: x part fine aggregate : y parts coarse aggregate, usually abbreviated as 1 : x : y . Occasionally, fine and coarse aggregates were combined in these mix designs. Early common mixing proportions for reinforced concrete were 1 : 3 to 1 : 6 (Boon, 1913), later 1 : 2 : 3 and 1 : 2 : 2, and for watertight structures 1 : 1, 5 : 2, 5 (Van der Schrier, 1938). In the 1930 and 1940 editions of the *Gewapend Betonvoorschriften* (G.B.V., Netherlands Code of Practice for Reinforced Concrete), examples for common concrete mixes are mentioned: 1 : 2 : 3 (cement content ca. 325 kg/m³) for normal structures, 1 : 1 : 1¹/₂ (cement content ca. 550 kg/m³) for watertight structures (e.g. reservoirs, basements), and 1 : 1¹/₂ : 3 (cement content ca. 350 kg/m³) for structures exposed to seawater. Compared to modern values, these values were high and will be discussed Section 5.2. The use of volume units was practical as the constituents were measured on-site, usually in wheelbarrows. To simplify the calculation of the material costs, the volume of cement was translated in bags of cement and kg (mass) (Boon, 1913). Other expressions for the concrete mix were kg cement per m³ sand, and kg cement per m³ hardened concrete (Bergsma & Homan van der Heide, 1910b; Christophe, 1905; Memmler et al., 1907). The quantity of mixing water was not addressed.

Before the introduction of the G.B.V., the preference of the construction company influenced the concrete mix design. Different proprietary reinforcement systems were known to use preferred concrete mixes, with Hennebique using a mix of 300 kg Portland cement : 0.40 m³ sand: 0.85 m³ coarse aggregate, Melan a 1 : 2 : 4 mix; Monier used for vaults 1 cement : 3 sand, resp. 450 kg cement/m³ sand (Christophe, 1905; van Rossum, 1902).

With the improved quality of raw materials and insight into concrete technology, the influence of the mix design and construction methods became more and more obvious. Abrams (1919) gave with his research theoretical support for the importance of the mix design, addressing problems such as “*what mix is necessary to produce concrete of proper strength for a given work*”, the best concrete at minimum costs for certain proportions, the role of different materials, the necessity to consider the water content and the influences of changes in the mix on the strength

of the concrete. He criticised the common “*method of arbitrary selection in which fixed quantities of fine and coarse aggregates are mixed without regard to the size and grading of the individual materials [...] All of the methods of proportioning concrete which have been proposed in the past have failed to give proper attention to the water content of the mix.*” (Abrams, 1919).

This research represented a turning point towards scientific-based concrete mix design. The dissemination of a more scientific approach to design the concrete mix can be noticed from the late 1920s on in Dutch textbooks. However, this knowledge was not always applied. Cases of significantly weaker concretes than expected from the used raw materials indicated that too little attention was sometimes given to a good design mix (Zwolsman, 1940). Counter measurements were the more structural application of construction site supervision, which included a control of the raw materials and their proportioning. In the 1920s, the importance and tasks of construction site supervisions were propagated (see for example Scharroo, 1929) and first mentioned in the G.B.V. 1940.

Scharroo (1946) was positive about the development starting in the 1930s of not only considering the strength of the cement when evaluating the quality of the concrete. Instead, the mix design was taken into account and the way of construction when discussing the quality of concrete. In practice, mistakes still happened when designing the mix and mixing the concrete (Zwart, 1961). As the concrete was mixed on-site, the actual mix design and thus the concrete quality could have been influenced by several factors. Only with the introduction of ready-mixed concrete plants from the late 1940s onwards a consistency in the quality and mix design was achieved on a large scale (see Section 2.3 *Historical context and material properties*). Other technological progresses influenced the mix design as well. After the Second World War, mechanical compaction methods were introduced on a larger scale and allowed a lower water content (Visser, 1950).

In the following sections, the fluctuations over time regarding the cement content (Section 5.2), the increasing understanding of the importance of mixing water (Section 5.3) and the main admixtures and additives used for historic concrete (Section 5.4) are discussed in detail.

5.2 Cement content

The cement content is the “*quantity of cement contained in a concrete [...] preferably expressed as mass per unit volume of concrete*” (ACI, 1990). In the present day standard NEN-EN 206-1:2005 *Concrete*, the minimum cement content depends on the degradation risks in relation with the exposure class of the concrete: 260-300 kg/m³ for concrete exposed to carbonation-induced corrosion, 300-340 kg/m³ to chloride induced corrosion, 300-340 kg/m³ to freeze-thaw attack and 300-360 kg/m³ to aggressive chemical environments. Initially, the exposure class did not influence the cement content, which was a balance between costs and strength. It was usually not expressed in kg/m³ but in volume parts in relation

to fine and coarse aggregates. In the G.B.V., the minimum cement content was expressed in kg cement per hl sand in the first five editions, and only in the last edition from 1962, was it expressed in kg cement per m^3 concrete (Table 5.1). Prior to the introduction of the G.B.V. in 1912, a minimum cement content of 280 kg/m^3 concrete was advised (Boon, 1908). The minimum cement content was temporarily reduced in 1941 during the Second World War to 300 kg/m^3 for normal structures and to 375 kg/m^3 for structures exposed to marine environments (Van der Schrier, 1942).

The cement content was chosen by the required quality and strength of the concrete, and its workability (Boon, 1913). Other factors influencing the cement content were the aggregate size and proportions of the concrete element. Finer aggregates required a higher cement content due to the higher surface area (Memmler et al., 1907). For the workability of the concrete, an early rule-of-thumb was that the more slender the concrete elements were, the richer the concrete had to be (Boon, 1913, 1931). In the 1930s a change can be noticed as the exposure conditions are considered when determining the required cement content. The G.B.V. 1930 demands for the first time a higher cement content for elements exposed to aggressive environments (see Table 5.1), hereby understood as exposed to sea water or other not further defined aggressive water. For exterior elements a higher cement content was preferred as to protect the reinforcement (Boon, 1931).

Following the then contemporary mortar terminology, concrete with a high cement content was called *vette beton* (rich concrete). The threshold for rich concrete varied, for example 325 kg/m^3 (Van der Schrier, 1942), 350 kg/m^3 (Zwolsman, 1940) or 375 kg/m^3 (Van der Schrier, 1960); expressed in volumes 1 : 6 (Boon, 1908), respectively 1 : 5 (Boon, 1931). A unique example for an unusually high cement content is Radio Kootwijk (1920-1923), a former short wave transmitter (Figure 5.1). The function of the building and the involved high voltages influenced several details of the reinforced concrete structure, especially of the reinforcement. To avoid disturbances in the transmitting, the reinforcement was not allowed to be continuous and the concrete had to be poured and compacted in several only 20 cm high pours to control the position of the reinforcement bars during construction. In addition, the amount of reinforcement was rather high. Therefore, the fresh concrete had to be rather plastic and when hardened strong enough to withstand the shear stresses at the numerous construction joints; a cement content of 600 kg/m^3 was therefore chosen for the roof beams (Emmen, 1923).

Concrete with a lower cement content was called *magere beton* (lean concrete). The threshold for a lean concrete varied between 275 kg/m^3 and 300 kg/m^3 . For plain concrete structures such as vaults, a lean concrete with a cement content of $240\text{--}250 \text{ kg/m}^3$ was advised, for non-structural elements even lower cement contents (Boon, 1908). A common application of lean concrete was for fillings above concrete arches. Van der Schrier (1938) advised a cement content of $245\text{--}277 \text{ kg/m}^3$ for plain concrete, vaults and tampered concrete with a cement-aggregate ratio of 1 : 6 to 1 : 7,5.

Table 5.1 Minimum cement content demanded in the different editions of the Gewapend Betonvoorschriften (G.B.V., Netherlands Code of Practice for Reinforced Concrete).

	minimum cement content	Proportions sand and coarse aggregates	Exposure class	Concrete type	Water content
G.B.V. 1912	135kg/2hl sand	1 : 2 – 1 : 1	n/a	n/a	n/a
G.B.V. 1918	125kg/2hl sand (1 : 2) 250kg/3hl sand (1 : 1 – 1/2)	1 : 1 – 1 : 1 1/2 Max. 1 : 2	n/a n/a	n/a n/a	n/a n/a
G.B.V. 1930	125kg/2hl sand 250kg/3hl sand 250kg/3hl sand	1 : 1 – 1 : 1 1/2 Max. 1 : 2 none mentioned	n/a n/a ▲	n/a n/a n/a	n/a n/a n/a
G.B.V. 1940	125kg/2hl sand 250kg/3hl sand 250kg/3hl sand	1 : 1 – 1 : 1 1/2 Max. 1 : 2 none mentioned	n/a n/a ▲	n/a n/a n/a	†
Decree July 1942 (reconstruction period) ^a	300kg/m ³ concrete 375 kg/m ³ concrete	125 kg cement : 2 1/4hl sand : 3 1/4hl gravel 125 kg cement : 1 3/4hl sand : 2 1/2hl gravel	n/a ▲	n/a n/a	†
G.B.V. 1950	125kg/2hl sand 250kg/3hl sand 250kg/3hl sand	1 : 1 – 1 : 1 1/2 Max. 1 : 2 1 : 1 – 1 : 1 1/2	n/a n/a ▲	n/a n/a n/a	†
G.B.V. 1962	Min. 325kg/m ³ Increase possible	replaced by fineness modulus	K225 K300	max.0.60 max.0.55	
Comparison					
NEN 5950:1995 (VBT 1995)	150-300kg/m ³ 260-300kg/m ³	Grading influences the cement content; gap grading requires higher content	Environmental classes 1-5 influence cement content	plain concrete reinforced concrete	max. 0.70; depends on exposure class 0.45 – 0.65; depends on exposure class

Legend: ▲ sea water or other aggressive waters; † none specified but consistent plasticity of concrete paste required.

^aDecree made by *Algemeen Gemachtigde voor den Wederopbouw en voor de Bouwnijverheid* (Van der Schrier, 1942).



Figure 5.1 Interior view of the main hall of Radio Kootwijk (J. Luthmann, J. Emmen, 1920-1923, situation 2006).

When comparing different mixes based on volumes suggested for concrete during time, a consistency in cement content for the same mixing proportions cannot be identified. In Table 5.2, an overview is given of the main concrete mixes mentioned in historic concrete textbooks; a more detailed overview including less common mixes is included in Appendix D. For lean mixes (mix proportions 1 : 6 and above), the differences in cement content are less, yet the richer mixes show a significant decrease of cement content of 10 – 20%.

The mixes usually refer to the use of gravel as coarse aggregate, except Scharroo (1942b), who differentiated between gravel and crushed stone, showing that crushed stone did require a higher cement content for rich concrete mixes (see Section 4.3 *Coarse aggregates*). In general, the cement content decreased with time. Initial causes were improved raw materials and construction methods (Memmler et al., 1907); fluctuations in the weight of cement itself were not uncommon before the introduction of standards for cements, for example: 135-145 kg/hl (Boon, 1908, 1913, 1920), 135 kg/hl (Minister van Oorlog, 1906; Scharroo, 1910a), 125 kg/hl (G.B.V. 1918) and 115-135 kg/hl (Boon, 1931). Later decrease of the cement content per m³ concrete was caused by increasing insight into mix design, grading of aggregates and determination of the water-cement factor.

In historic textbooks, the cement content can vary among contemporary publications. For example Boon's values from the 1908 edition indicate a lower cement content for the same mix proportions than the mixes suggested by Scharroo in 1910. Only from the 1930s, the differences between the different authors and editions become less, reflecting the application of standards and increased insight into concrete technology.

Table 5.2 Overview of the main concrete mixes described in Dutch textbooks.

Proportions cement:aggregates	Cement	Fine aggregate	Gravel	$\frac{\text{kg Cement}}{\text{m}^3 \text{ concrete}}$	Reference
1:5	1	2	3	390	Boon (1908)
				335	Boon (1913, 1920); Scharroo (1921)
				350	Dwars (1923)
				324	Bergsma (1934); Boon (1931); Van der Schrier (1938, 1942, 1949)
				322	van Dijk & Van der Baan (1952)
				330	Scharroo (1942b)
				430	Boon (1908); Dwars (1923)
1:4	1	2	2	420	Boon (1908, 1920); Scharroo (1921)
				388	Bergsma (1934); Boon (1931); Van der Schrier (1938, 1942, 1949)
				380	van Dijk & Van der Baan (1952)
				400	Scharroo (1942b)
				420	Boon (1920); Scharroo (1921)
				388	Bergsma (1934); Boon (1931); Van der Schrier (1938, 1942, 1949)
				382	van Dijk & Van der Baan (1952)

In order to convert concrete mixes mentioned in historic documents, it is necessary to consider the way in which the concrete mix and cement content was expressed. For example, for the Hofplein railway viaduct in Rotterdam the concrete mix was expressed in kg cement in relation to the volumes of the sand and gravel, and not in relationship to the volume of the concrete; the main concrete mix was 450 kg Portland cement : 0,5 m³ river sand : 1 m³ gravel (Braak, 1907). It was estimated then that for 1 m³ of concrete, 1,35 m³ sand and gravel in the proportions 1 : 2 was necessary (Scharroo, 1910a), resulting in a cement content of 400 kg/m³. An exact determination based on historic document alone is not possible, as the aggregate mix was not graded, the volume of cement not consistent and the water content unknown. However, it can be concluded that the cement content was high. Another example of different concrete mixes used for the forts of the Stelling van Amsterdam is given in Table 5.3. Using the information from Table 5.2 and Appendix D, an approximation of possible cement content can be made and the use of the different mixes indicated.

Table 5.3 Concrete mixes used for some plain concrete forts of the Stelling van Amsterdam.

Concrete type	Binder : aggregate ratio	Cement	Sand	Coarse aggregate	Fort Vijfhuizen ¹	Fort Bezuiden Spaarndam ²	Fort Benoorden Spaarndam ³	Fort near Hoofddorp ⁴	Approx. Cement content kg/m ³
Portland cement and gravel	1 : 9	1	3	6				✓	210
	1 : 7 ^{1/2}	1	2 ^{1/2}	5		✓	✓	✓	225 – 250
	1 : 7	1	2 ^{1/3}	4 ^{2/3}			✓		240
	1 : 6	1	2	4		✓	✓		300 – 318
	1 : 5	1	2	3	✓				335 – 390
	1 : 4 ^{1/2}	1	1 ^{1/2}	3		✓			370 – 450
Portland cement and porphyry	1 : 4	1	1	3	✓				420
	1 : 7 ^{1/2}	1	2 ^{1/2}	5				✓	≥ 225 – 250
	1 : 7	1	2 ^{1/3}	4 ^{2/3}		✓			≥ 240
	1 : 6	1	2	4		✓	✓	✓	≥ 300 – 318
	1 : 4 ^{1/4}	1	1 ^{1/4}	3				✓	> 370 – 450
	1 : 4 ^{1/2}	1	1 ^{1/2}	3		✓	✓		> 420
Cement and broken bricks	1 : 4	1	1	3		✓	✓		> 420
	1 : 7	1	2 ^{1/3}	4 ^{2/3}		✓			no ref.

Information on the original cement content of historic concrete can be necessary for the assessment of the degradation risk as it influences the durability of concrete. A high cement content might counteract the effects of carbonation, yet in combination with some degradation mechanisms a high cement content can be harmful (Grantham, 2011d). For example, for alkali-silica-reaction (ASR), the alkalis from the cement, besides reactive aggregates, are involved, and a higher cement content can support the reaction for a longer period. A high cement content can also indirectly increase the risk and severity of some reactions. A high addition of gypsum was sometimes advised as a catalyst for blast furnace slag cement, and in case the cement content was higher, more gypsum would be present in the concrete (see Chapter 3.8.3 Hoogovencement (*Blast furnace slag cement*)). This has to be considered, as a sulphate attack can cause a secondary ettringite formation.

¹According to construction drawings from 1897

²According to construction drawings from 1900

³According to construction drawings from 1900

⁴According to construction drawings, built 1903-1904

5.3 Mixing water

Water is necessary for the hydration of the cement and, besides cement and aggregates, it is one of the main constituents of concrete. For the workability of the fresh concrete and the durability of the hardened concrete, the quality (Section 5.3.1) and quantity (Section 5.3.2) of the mixing water is relevant. Water was usually only quickly addressed in textbooks and in the G.B.V.'s, and thereby mainly focussing on the workability of the fresh concrete and on suitable water sources. A scientific approach towards determining the required quantity of water emerged in the Interwar period. Only with the dissemination of Abrams' (1919) research on the concrete mix design, the importance of the mixing water was wider discussed.

5.3.1 Quality of the mixing water

The quality of the mixing water influences both the properties of fresh concrete, especially its setting, and the durability of the hardened concrete as possible impurities can cause deterioration (e.g. sulphate attack, chloride induced corrosion). Mixing water is now classified according to its origin: potable water, water recovered from processes in the concrete industry, water from underground sources, natural surface water, industrial waste water, sea water or brackish water, and sewage water (NEN-EN 1008:2002). As the quality of the mixing water influences the durability of the concrete, only potable water can be used without further testing. Water containing chloride such as sea water or brackish water should only be used for plain concrete structures due to the corrosion risk. The quality of other water classes, except sewage water which is not suitable in general, should be tested for their suitability for the production of concrete. The assessed aspects of the water are its chemical properties (chlorides, sulphates and alkali content), the presence of harmful contaminations (sugars, phosphates, nitrates, lead, zinc), and its influence on the setting time and strength.

Early requirements towards the quality of the mixing water were its cleanness and freshness. It was advised to visually inspect the water to check if it was turbid and for floating particles, and if the result were not satisfactory, the water could be filtered in sand (Minister van Oorlog, 1906, §176). In the G.B.V. 1912, mixing water was only addressed in context with the mixing of the concrete. The water was either required to be free of harmful elements (G.B.V. 1912, art. 5) or clean fresh water (G.B.V. 1918, art. 5). In the 1930 edition, water was addressed for the first in an own article (G.B.V. 1930, art. 7) and the scope widened to mixing water and water for keeping the concrete wet; the requirements towards the quality remained the same with using clean fresh water. Only in the G.B.V. 1962, the article was altered with the emphasis now on that the water should not contain any substances which are harmful for the concrete. The types of harmful substances were not mentioned, neither a threshold given as it was done in more recent standards (for example NEN 5995:1988).

Although not mentioned in the G.B.V., different harmful substances in the mixing water were discussed in textbooks. The water should be free from organic matter such as peat and plant fibres, coal particles, and not be contaminated with gypsum (sulphates) or magnesia (Bergsma & Homan van der Heide, 1910b). A contamination with sulphates could lead to the deleterious formation of gypsum in the concrete (now called delayed ettringite formation; Boon, 1931); it should not contain silt or clay particles, acids, salts, sulphates or humic matter (Van der Schrier, 1938). A chemical analysis of water was advised if the water had an unpleasant odour or taste, was impure, turbid or coloured (Scharroo, 1949). The use of salt contaminated water was discouraged for exposed concrete as it can cause efflorescence (CUR report 36,1966). The mixing water should neither be too warm nor too cold to not affect the setting of the concrete (Bergsma & Homan van der Heide, 1910b).

Besides tap water, which was not everywhere available, usable water types were rain water, water from wells, rivers and lakes; unsuitable was sea, peat and marsh water (Bergsma & Homan van der Heide, 1910b). Sea water was not considered harmful because of the risk of chloride corrosion, but of the destructive properties towards calcium carbonate in the binder and the occurrence of efflorescence on the surface, and the hygroscopic properties of the salt which would maintain the concrete wet (Ast, 1907; Memmler et al., 1907). Positive experience was made in the Netherlands with the use of sea water as mixing water in combination with the use of trass-bearing cement (Probst, 1917). River water was considered usable, but warnings were given for not using water from canals or ditches near factories without testing (Van der Schrier, 1938). Although it was common knowledge that only clean and clear fresh water should be used, cases of using unsuitable water were not uncommon, especially if it was easily available in ditches or puddles (see Figure 5.2, and Scharroo, 1949).

5.3.2 Quantity of mixing water

The ideal water content is high enough to allow a good workability of the concrete, yet low enough to not negatively affect its quality (e.g. strength, resistance). Initially, the workability of the concrete was the main criterion for the water content. Early textbooks did not address the water content or if so, only quickly suggested to use as little water as possible (for example Reid, 1869, 1879). For plain concrete, a concrete with little water content was usable but with the increase use of reinforced concrete this practice was later reviewed.

As no general scientific rules for an ideal water content existed at the beginning of the 20th century, the water content was determined empirically (Bergsma & Homan van der Heide, 1910b; Memmler et al., 1907), and could be influenced by the preference of the building site manager (Christophe, 1905). Other criteria were the properties of the cement and of the aggregates, the concrete mix, the construction method, the temperature and weather during hardening, and the type of concrete works (Scharroo, 1949). The water content was commonly expressed



„Wou je soms met die modder beton gaan maken?”

Figure 5.2 Illustration addressing the use of contaminated mixing water. “Where you perhaps planning to make concrete with this mud?” (Scharroo, 1929, p. 51).

in weight percentage of the dry mix (binder and aggregates); the water present in the aggregates was hereby considered (Bergsma, 1934; Memmler et al., 1907). Before the application of the water cement factor in the 1930s, the percentage was sometimes expressed in volume (Bergsma & Homan van der Heide, 1910b; Scharroo, 1927b, 1949).

The transition from an empirically determined water content to a scientifically approach started already in the late 19th century. In 1896, Féret carried out experiments to determine the desired consistency of mortar, such as plastic or dry consistency (Neville, 2008; Taylor & Thompson, 1905). Abrams (1919) investigated the relationship between the concrete mix design and the compressive strength of the concrete, and showed that the water content was a very important variable for the strength of the concrete. His ground breaking discovery was of a formula which could help to determine the desired concrete strength depending on the proportions between cement and water content, the so called cement-water ratio: “The water content of a concrete mix is best considered in terms of the volume of the cement - the water ratio.” (Abrams, 1919).

In the United States of America, the cement-water ratio was initially based on volume, whereas in the Netherlands and in Europe it was based on weight and called the water-cement factor (CUR report 1, 1955; Scharroo, 1949). The use of weight instead of volume was considered better, as the weight of different cement types varied (Zwolsman, 1940). The water-cement factor was a new concept, which replaced former concepts of using percentages based on weight (Figure 5.3) or volume (Figure 5.4) to determine the water content (see also Table 5.4). The

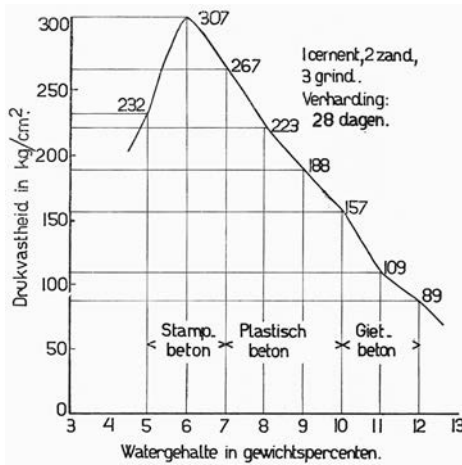


Figure 5.3 Water content in percentage (weight) in relationship with the compressive strength kg/cm² and classification of workability (Scharroo, 1949).

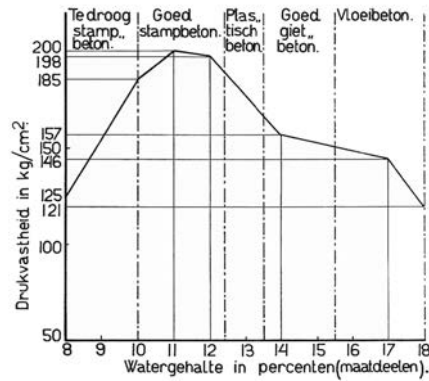


Figure 5.4 Water content in percentage (volume) in relationship with the compressive strength kg/cm² and classification of workability (Scharroo, 1949).

water-cement factor (w.c.f) is still applied and considered as one of the most important criteria for the strength of the concrete; not only the directly added water is considered, but the total water content: the mixing water plus the water in and on the aggregates, plus the water in admixtures and additives, plus the water in form of ice and steam. It is defined as the “*ratio of the effective water content to cement content by mass in the fresh concrete*” (NEN 5960:2006). To determine the water-cement factor (w.c.f.), the weight of effective water content (W), which is the water in the concrete mix without the water absorbed by the aggregates, is divided by the weight of the cement (C):

$$w.c.f = W/C \quad (5.1)$$

The water-cement factor lay most commonly between 0,35 and 1,0, which corresponds with the classes of tampered concrete to liquid concrete (Scharroo, 1949; van Dijk & Van der Baan, 1952; Zwolsman, 1940). The range of the used factors differed from present day recommendations. Today, a water-cement factor of 0,40 is considered as the minimum water content required for hydration, and in practice values between 0,42 and 0,70 are used (Wendehorst, 2004). The exposure class of the concrete structure was initially not considered when determining the water-cement factor. In the present day standard EN 206-1:2000 *Concrete*, the maximum water-cement factor is related to the exposure class of the concrete, with 0,50–0,65 for concrete exposed to carbonation-induced corrosion, and 0,45–0,55 to more severe exposure classes such as chloride-induced corrosion, freeze-thaw attack and aggressive chemical environments. The water-binder factor, which uses

the content of both cement and fillers, instead of only the cement, did not play a role in the mix design of historic concrete.

Although Abrams' research was quickly spread and published in textbooks, the following of these new design rules to use a specific water content required more persuasion than as it had for the use of a specific cement content to achieve a good concrete (Scharroo, 1949). All too often, a too high water content was used to reduce the costs and to ease the construction works (Scharroo, 1946). Following properties of the constituents could require a higher water content: the use of crushed stone, a higher porosity of the aggregates, higher quantity of fine aggregates, a lower cement content, and the use of finer cements and rapid hardening cements (Probst, 1935; Scharroo, 1927b, 1949). In the 1920s, the use of new machines to facilitate the construction works, such as the concrete pump, the use of conveyor-belts or chutes, replacing the use of wheelbarrows, influenced the construction methods strongly and by this the desired workability of the concrete (Bergsma, 1934; Scharroo, 1927b,c).

Before the application of mix design rules, the workability of the fresh concrete was the main aspect and its consistency was mainly discussed. The terminology for fresh concrete was influenced by both, the consistency and the method of placing or compacting. It was classified as dry mix for plain tampered concrete and a more liquid, plastic concrete for reinforced concrete; a third class was the so-called *gietbeton* (liquid concrete) for reinforced concrete, which was not so appreciated in terms of quality (Table 5.4 and Figure 5.5). The tools for compaction were chosen depending on the consistency of the concrete, drier mixes were tampered or rammed (*stampen*), wetter mixes puddled (Taylor & Thompson, 1905).

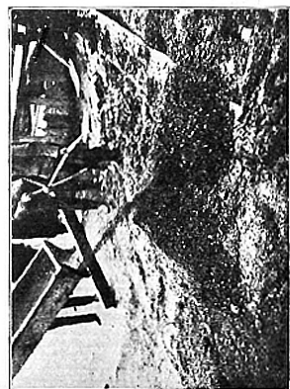
For plain concrete, with no disturbing reinforcement during placing and compacting the concrete, a rather dry mixed was advised, and the concrete called **stampbeton** (**tampered concrete**). A very low water content was recommended as otherwise the concrete would show too much shrinkage (Van der Kloes, 1893). The consistency of the water-cement mix should be similar to a humid powder, of the concrete similar to freshly dug, damp earth (Boon, 1931; Taylor & Thompson, 1905; Van der Kloes, 1893) or of “*tenacious, jelly-like*” consistency (Taylor & Thompson, 1905). The Dutch term *stampbeton* was replaced during time with *aardvochtig beton* (earth humid concrete).

The use of such a dry concrete was only recommended when a good execution and supervision of the construction works, especially of the compaction, was secured (Memmler et al., 1907). The compaction was difficult and it was harder to obtain a uniform consistency as some batches would be too dry and it was “*impossible with ordinary care in placing and ramming to avoid visible voids or pockets of stone which form weak places and allow the penetration of water*” (Taylor & Thompson, 1905). An indication for good compaction was the appearance of surface water only after a long period of tampering (Bergsma & Homan van der Heide, 1910b; Memmler et al., 1907). Due to its consistency it could only be used for plain concrete and not for reinforced concrete.

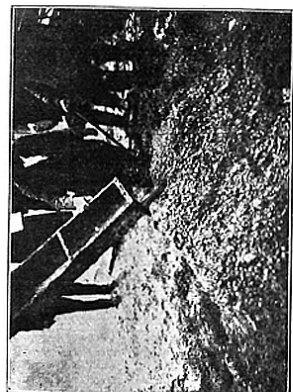
Table 5.4 Overview of the water content of different concrete consistencies mentioned in historic Dutch concrete textbooks.

	Tamped concrete		Plastic concrete		Liquid concrete	
	%weight	%volume	%weight	%volume	%weight	%volume
Bergsma & Homan van der Heide (1910b)	12-17					
Scharroo (1927b)	10-12		12.5-13.5		13.5-15.5	
Boon (1931)	5-7.5		7.5-10	150-200	10-13.5	200-285
Bergsma (1934)	6-8	0.4-0.6	8-10	0.6-0.8	10-12	0.8-1.0
Van der Schrier (1938)	6-8		8-10		10-14	
Scharroo (1949)	5-7	10-12.5	7-9	12.5-13.5	10-12	13.5-15.5
van Dijk & Van der Baan (1952)		0.35-0.50	8-10	0.5-0.65	10-14	0.8-0.9
Van der Schrier (1953)	6-8	0.4-0.6	8-10	0.65-0.75	10-14	0.8-0.9
Van der Schrier (1968)		0.25-0.3 ^a		0.45-0.65		0.55-0.7
		0.3-0.5 ^b				

^a Tamped
^b Vibrated



Afb. 2. Te droog stampbeton.



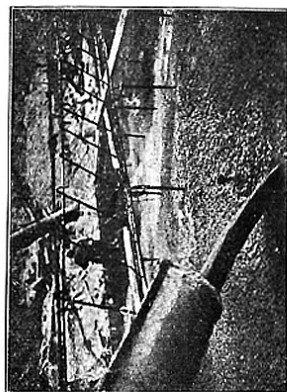
Afb. 3. Goed stampbeton.



Afb. 4. Plastisch beton.



Afb. 5. Goed gietbeton.



Afb. 6. Grens tusschen gietbeton en te nat beton.



Afb. 7. Te nat beton.

Figure 5.5 Different consistencies of fresh concrete (Scharroo, 1927b, p. 305): (top left to right): too dry tamped concrete, good tamped concrete, plastic concrete; (bottom left to right): good fluid concrete; borderline between fluid and too wet concrete; too wet concrete.

The use of tampered concrete decreased at the beginning of the 20th century, as it was too difficult and time costly (Bergsma & Homan van der Heide, 1910b; Memmler et al., 1907). Concrete with a low water content was later still applied for small precast concrete elements (Van der Schrier, 1953), and for *schokbeton*.⁵ *Schokbeton* is a precast concrete, which was compacted by being placed on a vibration table; such concrete required a good concrete mix design and allowed the use of a very low water-cement factor of 0,3 – 0,35 (Scharroo, 1946).

For reinforced concrete, **plastic concrete** (*plastisch beton*; “*very wet or mushy concrete*” (Taylor & Thompson, 1905)) was advised, which had a higher water content. The consistency was compared to thick mud (Bergsma & Homan van der Heide, 1910b). This was necessary as the reinforcement hindered the pouring and the compaction of a too dry concrete; tampering could harm the reinforcement (Christophe, 1905). The use of plastic concrete for reinforced concrete was advertised as it could enclose the concrete better than a dry mix. However, warnings were given of not using a too liquid concrete such as *gietsbeton* which would reduce the density and strength of the concrete (Scharroo, 1910a). Plastic concrete was suitable for reinforced concrete as it was liquid enough to flow yet did not segregate during transport (Boon, 1931; van Dijk & Van der Baan, 1952). At 0,6 – 0,8, the water cement factor of plastic concrete was high. Only in the 1950s, the introduction of plasticisers allowed to reduce the water cement factor while improving the workability of concrete (see Section *Admixtures and additions* 5.4).

A very liquid concrete of a fluid consistency was *gietsbeton* or *vloeibaar beton* (cast or fluid concrete), which flowed due to its own weight. It was used for reinforced concrete, especially for elements which were harder to compact, or to reduce the costs of the construction works by minimising the amount of work required for compaction. Warnings were expressed against its use, as the concrete would be of a lower strength and density (Scharroo, 1910a, 1916, 1927b). However, as it was easier to compact and possible to pump, a technique which emerged in the 1920s, the lower strength was taken into account. For being able to be pumped, *gietsbeton* required at least a sand content of 50% and a surplus of cement to avoid segregation (Bergsma, 1934). It was still discussed in the Post-War years for reinforced concrete, yet mainly its disadvantages were addressed such as the required high cement content, its lower strength, reduced watertightness, the risk of strong shrinkage, segregation and a leaking of the concrete through the formwork (van Dijk & Van der Baan, 1952).

The water content was initially not addressed in the G.B.V. In the G.B.V. 1940, the plasticity of the concrete, which is influenced by the water content, was addressed for the first time. It was recommended that it had to be consistent for

⁵Schokken is a Dutch patented compaction method for prefabricated concrete elements (Patent number No. 36029, July 1934) and produced by the company *N. V. Schokbeton*. The concrete was compacted by hitting the formwork several times quickly on a special developed table (see Grin & van der Veen, 1950; Scharroo, 1944, 1946; Wattjes, 1936). The produced concrete was called Schokbeton. It was often used in the post-war reconstruction period. The term Schokbeton is now sometimes wrongly used as a synonym for prefabricated historic concrete.

a structure. The quality control of fresh concrete should be done with Abrams' slump test with a cone and with flow tables. In textbooks, the use of these tests to evaluate the consistency had been discussed before (for example Bergsma, 1934; Boon, 1931). Only in the G.B.V. 1962, a water-cement-factor was demanded for the first, with a maximum water-cement factor of 0,6 for the quality class K 225, and 0,55 for a K 300 concrete. The now maximum water-cement factor of 0,6 was considered previously as the lower limit for a concrete useable for reinforced concrete, and values below only useable for plain and tampered concrete structures. The overall decrease of the water-cement factor can be explained with improved compaction methods (mechanical instead of manual), improved grading of the aggregates and the introduction of plasticisers in the late 1950s.

5.4 Admixtures and additions

Admixtures and additions are fine materials added to the concrete before or during mixing to modify the properties of either the fresh or hardened concrete. Their use for concrete was mainly based on three goals: either to reduce the costs, ease the construction (placing, setting, hardening of the concrete) or to improve the durability of the concrete in aggressive environments such as sea water. The distinction between additives and admixtures varies in literature and standards. In historic concrete textbooks, no differentiation was made, and combined as *hulpstoffen* (additives). The use of admixtures and additions is mentioned for the first in the G.B.V. 1962, yet they are only quickly addressed without any classification of types of admixtures and maximum contents.

In present day standard for NEN-EN 934-2:2009 *Admixtures for concrete, mortar and grout*, admixtures are defined as “*material added during the mixing process of concrete in a quantity not more than 5% by mass of the cement content of the concrete, to modify the properties of the mix in the fresh and /or hardened state*”. The present day standard NEN-EN 206-1:2005 *Concrete*, defines additions as “*finely divided material used in concrete in order to improve certain properties or to achieve special properties. This standard deals with two types of inorganic additions*”:

- *nearly inert additions (type I);*
- *pozzolanic or latent hydraulic additions (type II)."*

Other differentiations are based on the percentage, with less than 5% considered as an admixtures, with more than 5% as additive (Ramachandran, 1995).

Referring to the differentiation used in NEN-EN 934-2:2009 and its Dutch predecessor NEN 3532:1995, the following classes of admixtures were the most commonly applied and discussed in the Netherlands: accelerators, retarders, air entraining agents and plasticisers. The main additions were pigments (see Section 7.5.1), fillers, and pozzolanic or latent hydraulic additions (see Section 3.9).

The acceptance of admixtures and additions faced many prejudices due to the debasing of expensive Portland cement with cheaper material at the end of the 19th century. Exceptions were gypsum, which is strictly speaking not an additive as it is directly mixed into the cement (see Section 3.5), and pigments (see Section 7.5.1). The initial difficulties to determine admixtures in cements increased doubts and initiated the definition of Portland cement. Ground slag, trass, and ground brick were seen as fillers and their use not allowed as they apparently did not improve the quality of the Portland cement (Ast, 1907; Van der Kloes, 1893). With the increase use of concrete and experience with the construction of concrete structures and their durability, insight was gained that admixtures could be beneficial. One main impulse was to improve the durability of concrete for marine structures, where positive experience was gained with the use of slags and trass.

The wish to shorten the binding time of concrete and to be able to carry out works during low temperatures led to the use of accelerators. Therefore, different types and quantities of salts were used. The quantity of the chlorides was expressed in percentage, either referring to the mass of mixing water or of the cement, yet sometimes no reference was mentioned: 0,5% of soda (Na_2CO_3), up to 5% of common salt (NaCl , sodium chloride) or up to 4% of calcium chloride (CaCl_2) (Boon, 1913; Boon, 1931; Burchartz et al., 1927; Probst, 1935; Scharroo, 1946).

Research on the benefits of adding chlorides, and hereby mainly calcium chloride (CaCl_2), emerged on larger scale in the 1920s. Calcium chloride became the most common salt used as an accelerator as it was the cheapest (De Kuijper, 1962). The use of calcium chloride to improve the setting and hardening of concrete was already patented in 1885 in England by W. Millar and C.F. Nichols. (van de Fliert, 1962). The use of soda for bedding mortars made with Portland cement when working during frost was already occasionally carried out (Van der Kloes, 1908c). The adding of salts to allow construction during low temperatures became common knowledge during the first decades of the 20th century. Other advantages of adding calcium chloride were, as the concrete set and hardened quicker, a quicker production line of precast concrete elements as the formwork could be struck sooner. These properties made its use attractive for construction works with a limited period of time available, such as repair of bridges or constructing in tidal zones. An admixture of 1 – 2% of calcium chloride by mass of the cement was the most common quantity, sometimes 3% and for casting during low temperatures even up to 4% were used (Scharroo, 1953).

However, in the 1950s the possibility of chloride induced corrosion started to draw attention (Theissing, 1961; van de Fliert, 1962). It was concluded that a calcium chloride content of 2% by weight of the cement would not cause corrosion if the concrete was of a good quality. A code, *Voorschrift tot het gebruik van calciumchloride in beton*, was published to supplement the G.B.V. 1950 resp. 1962, addressing the use of calcium chloride in concrete. It allowed a max. 1,5% pure calcium chloride by mass of the cement, in combination with a minimum cement content of 325 kg/m³ concrete and a maximum of 375 kg/m³ concrete. Calcium chloride could be added to Portland cement, blast furnace slag cement

and Portland-slag cement. The calcium chloride was to be dissolved in the mixing water and added to the mix (De Kuijper, 1962).

Scharroo (1946) criticised the practice of adding 5 – 10%⁶ of common salt (NaCl) to prevent the mixing water from freezing for temperatures between –5 to –8°C, as it could cause corrosion of the reinforcement and decrease the strength of the concrete. Other risks were increased shrinkage when adding 2 – 4% by mass cement of calcium chloride in the mixing water.

The use of admixtures containing chlorides for concrete with embedded steel is not permitted any more as the chlorides can induce corrosion; nowadays, the chlorides present in the constituent materials should not exceed 1% chloride by mass of cement for plain concrete, for reinforced concrete not even 0,4% resp. 0,2% for pre-stressed concrete depending on the use (NEN-EN 206-1:2005). These values show that the previously used percentages of chlorides are rather high and therefore indicate that historic concrete made with accelerators can be prone for chloride induced corrosion. From experience of investigating structures with chlorides, a threshold for a possible deleterious chloride content around 0,4% by mass of the cement is suggested (Grantham, 2011d).

An example for the use of chlorides as accelerator and the resulting degradation is the *Dresslhuys pavilion* (Figure 5.6). The designer and engineer J.G. Wiebenga (1886-1974) published in 1925 about the use of calcium chloride as accelerator, indicating that its use was consciously and considered beneficial. The presence of chlorides has been stated in the roof slabs and led to the corrosion of the reinforcement bars (Henket & De Jonge, 1990). During a conservation campaign in 2008, the roof slab and lift shaft were therefore demolished and reconstructed.

A large-scale example of the application of calcium chloride as accelerator was for precast elements. A major problem with precast floor elements due to their quantity was encountered in the 1990s; between 1965 and 1983, the Dutch company *Kwaaitaal-Vormbeton B.V.* and between 1975 and 1981 the Dutch company *Betonindustrie Woerden B.V.*, produced precast floor elements with the use of calcium chloride for ground floors, the *Kwaaitaal-* resp. *Manta-vloer* (CUR, 2000). Other fields of application were for pre-cast cantilever beams for gallery slabs of apartment buildings from the 1960s-1970s.

Another common use for admixtures was to retard the setting of the concrete. Initially, the main type of retarder was gypsum and was the only admixture allowed for Portland cement. Nowadays, gypsum is not considered as an admixture anymore, but has become an essential part of the cement to retard the setting and is added during the manufacturing of the cement. The use is not limited to gypsum, but includes different forms of calcium sulphate (CaSO_4), such as hemihydrate, or anhydrite (NEN-EN 197-1:2011). Some less used retarders were phosphoric acid, nitrates, and lead and zinc compounds (Poels, 1958; v.d.V., 1957; Van der Schrier, 1968). The use of retarders was advised for exposed concrete when the surface was intended to be treated after striking the formwork (Van der Schrier, 1960), and

⁶Scharroo does not mention a reference of mass.



Figure 5.6 Example of corrosion induced by chlorides which were cast in to allow works during low temperatures. The historic concrete structure was demolished and reconstructed (*Dresselhuys pavilion*, part of *Sanatorium Zonnestraal*, Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928). a) Interior view of lift shaft before demolition, showing exposed reinforcement, cracking and efflorescence (January 2008). b) Exterior view of the reconstructed lift shaft (September 2008).

for mass concrete to prevent cracking due to the heat development during hydration (v.d.V., 1957). In early publications, the use of calcium chloride is mentioned as a retarder as well (Boon, 1913, 1920, 1931); this is chemically possible as with a calcium chloride content below 1% it reacts as a retarder, with higher contents as an accelerator (Ramachandran, 1995).

To improve the workability of the concrete, plasticisers and air entraining agents (*luchtblvormer*) are used. They became available after the Second World War. Plasticisers reduce the surface tension of the water, increase the workability of the concrete and allow the use of a lower water-cement factor. Their use was advised for normal concrete structures, as they were considered very beneficial (Van der Schrier, 1968). Air entraining agents improve the workability of the concrete while using a lower water-cement factor. They were already used in the 1940s in the USA and England and the concrete called air-entrained concrete. In the early 1950s, they were not applied yet in the Netherlands. In the late 1950s the interest in their use increased, and air entraining agents had been successfully used by then (Van der Schrier, 1960). The entrained air disturbs the capillary system of the concrete, and makes it thus more resistant to freeze-thaw damage. Other advantages were improved workability, lower risk of segregation, increased density and strength of the concrete as a lower water-cement factor could be used, no appearance of plastic shrinkage cracks, and better adhesion towards the reinforcement, yet its main disadvantages was its high price (van Dijk & Van der Baan,

1952). Too much air entraining agent can reduce the strength of the concrete, and a limit of 3 – 5% is advised. Air entraining agents are added when mixing the concrete in form of a liquid.

5.5 Conclusions

The different mix designs used for historic concrete reflect the growing experience and insight into concrete technology. The recognition of concrete as an entity of cement, both fine and coarse aggregates, and water and not only as a mortar to which coarse aggregates are added, is only one expression of the increasing understanding of concrete.

The growing interest into the mix design of concrete reflects that the quality of concrete does not solely depend on the quality and quantity of the used cement. Previously, individual research questions such as the required cement content, the optimal grading of the aggregates, the influence of the water content, and the options to reduce construction costs merged together in the mix design. As a result, the quality control of the concrete improved, better predictions of the quality of the concrete could be made, and the concrete mix design was optimised. The first major wide-scale breakthrough can be noticed in the 1930s, when improved construction methods showed the benefits of well-designed concrete mixes. Before that, fluctuations caused by poorer construction methods would have undone the improvements of carefully designed mix. In the 1950s, newly introduced admixtures such as plasticisers allowed further optimisation.

The details of concrete mix designs show much more variety as the commonly referred to “1:2:3”. Even for the same mixes, the concrete varied during time. Previously, the cement content was much higher, due to use of less fine ground cements, and due to the lacking of a grading of the aggregates.

The water content was initially high compared to modern standards. Reasons were not only limited insight into concrete technology but also less evolved construction methods. Again, only the combined progress of scientific insight and construction methods allowed an improvement of the concrete quality. Other beliefs in progress turned out to be unfortunate, with the use of chlorides as accelerators as the most known case.

Detailed information of the original mix design, additives and admixtures used is necessary when it comes to evaluate degradation risks (e.g. chloride induced corrosion, freeze-thaw) and to choose compatible repair mortars. The original mix design used cannot be identified simply on-site. The historic period (see Figure 2.15 *Timeline for the mix design for historic concrete*), the type of concrete element, the used aggregate, or the production method can give first indications. Samples can be further investigated for the original mix design. Microscopic investigations can identify the use of air entraining agents; the water-cement factor can be derived from the porosity of the concrete. Chemical analysis of the concrete can give information of the original cement content.

Chapter 6

Reinforcement

Chapter Outline

In the previous chapters the constituents and mix designs used for historic concrete in the Netherlands were discussed. In this chapter, historical aspects concerning the reinforcement used for historic reinforced concrete will be explained. The main focus will be on the identification of types of reinforcement, the obsolete terminology and the relevant durability properties influenced by the design.

6.1 Introduction

As concrete can only carry little tensile stresses, a concrete structure has to be designed either to carry only compressive loads, for example by using a vault structure (Figure 6.1), sometimes in combination with external iron profiles (Figure 6.2), or a reinforcement has to be embedded in the concrete to carry the tensile stresses (see Figures 6.3 and 6.4). The concept of embedding iron in masonry to carry tensile strengths was known and applied before the invention of reinforced concrete (Addis, 2007).

Much has been already written about the invention and origin of reinforced concrete, the different patent systems and the key figures such as Hennebique, Monier, or Lambot (for example Addis, 2007; Curbach et al., 2007; Huberti, 1964; Newby, 2001; Scharroo, 1946; Sutherland et al., 2001 and Von Emperger, 1904). Therefore, the types and details of the different reinforcement systems and patents, their commercial exploration, will not be further addressed in this thesis (see also Section 2.2 *Historical context*). Instead, the material aspects of the reinforcement are discussed, in particular as the materials used, iron or steel, the changes in terminology and classification, the geometry of the reinforcement, the connection of the reinforcement bars, and the concrete cover. Some of these topics, such as bars used



Figure 6.1 Example of a plain concrete vault (Fort near Vijfhuizen, 1899, situation 2006).

Trogwulven van beton tussen ijzeren I liggers

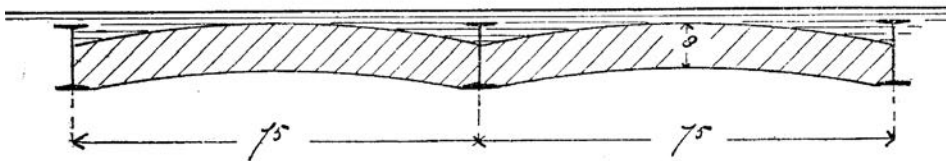


Figure 6.2 Schematic construction drawing of plain concrete vaults between iron I-section beams for floor constructions (Verhey, 1912, p. 154).

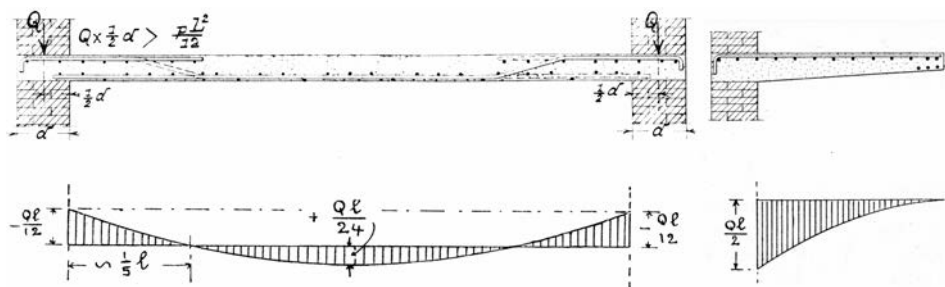


Figure 6.3 Systematic drawings of the location of the reinforcement in a slab and a cantilever in relationship with the bending moment (Bergsma & Homan van der Heide, 1910b, pp. 86 and 91).



Figure 6.4 Section through floor slab at a negative bending moment above a beam, showing two reinforcement layers: (red lines) at the top with larger cross sections and at the bottom with smaller cross sections, reflecting the bending moment (Philips Lichttoren, building EC, Eindhoven, A. Beltman, 1909-11, situation 2007).

and steel classification, have been recently outlined for the Dutch situation (Bot, 2009). Yet, the historical information is not always correct, such as the moment of introduction, terminology and understanding of the underlying principles and material changes. In this chapter, the Dutch construction history of reinforcement is therefore clarified. This information is relevant for historical surveys to correctly identify the used reinforcement on-site and understand the obsolete terminology in historic documents. Understanding the historical context and execution of the reinforcement is helpful as it is necessary to make assumptions of the geometry, quantity and position of the reinforcement when carrying out inspections, such as a cover meter survey which requires a calibration according to the assumed lay-out of the reinforcement (Grantham, 2011a).

Additionally, the material and construction aspects which influence the durability are outlined in this chapter and possible consequences for conservation discussed. Corrosion of the reinforcement is one of the main degradation mechanisms of reinforced concrete, and besides affecting the structural capacity of a structure, the damages symptoms (cracking, spalling) can cause a loss of a potential valuable surfaces and of historic material. Understanding the material properties is relevant as they influence the durability (for example corrosion behaviour of steel and iron, corrosion due to carbonation) and the possibilities of repair (for example welding, risk of galvanic corrosion, possibilities of cathodic protection).

The mechanical properties of the reinforcement, such as the yield strength, or the structural capacity of different reinforcement systems and the underlying theories, lay outside of the research scope of this thesis; for these topics other references should be consulted and their applicability for the Dutch situation evaluated (for example Clarke, 2004; Clarke, 2009; Fingerloos, 2009; Sutherland et al., 2001; Wapenhans & Richter, 2005).

6.2 Application and history of reinforced concrete

The principle of reinforced concrete is to combine the mechanical properties of concrete, which is stronger in compressive strength, and of iron, later steel, which is strong in tensile strength. Some non-structural, reinforced concrete systems were already patented in the middle of the 19th century as a substitute for wood (e.g. patents by the French Lambot and Monier) or as a fire-proof flooring system (see Section 2.2 *Historical context*). The breakthrough of reinforced concrete as a common building material started on an international scale in the late 1870s with Hyatt's publication on fire proof floor systems, Monier's patent from 1878 and Hennebique's application from 1879 onwards (Newby, 2001).

In the Netherlands, reinforced concrete was introduced by the Belgian company *Picha et frères*, patent holder of Monier's system in Belgium. They took advantage of the Dutch situation of not having a patent protection, and opened an agency in 1888 in the Dutch Province of Zeeland; the main product were water reservoirs (Foerster et al., 1912; Oosterhoff et al., 1988; Von Emperger, 1904). The

following Dutch reinforcement company which also used a Monier system was the *Amsterdamsche Fabriek van Cement-IJzerwerken "Wittenburg"*, founded in 1890. Sanders joined the company in 1895 and became its technical director. Sanders carried out several experiments on the behaviour of reinforced concrete and became one of the few internationally respected Dutch researchers on reinforced concrete (see for example Sanders, 1907).

Only from 1900 onwards, reinforced concrete became a material of more interest in the Netherlands, influenced by the World Exhibition in Paris and with the introduction of the Hennebique system in the Netherlands (Disco, 1990). Although the Netherlands did not have a patent system until 1912, a free application of reinforced concrete was difficult as the knowledge of how to calculate a reinforced concrete building was kept secret by the reinforcement companies. Only with the increase of publications, textbooks and the upcoming of code of practices, the knowledge was disseminated on a wider scale (see Section 2.2.2). In this context, the achievements of the Dutch military engineers in education, gaining of (empirical) knowledge and construction must be acknowledged.

The construction of the plain and reinforced concrete forts of the Stelling van Amsterdam overlaps with this period of knowledge dissemination, and emerge of theories of the calculation of reinforced concrete, and with the transition from plain concrete structures to reinforced concrete structures. For military defence structures advantages were seen in using reinforced concrete instead of the previously plain concrete structures. Reinforced concrete reacted better as a monolithic structure during an impact, as the reinforcement bridged cracks, which were unavoidable during the construction (e.g. construction joints, shrinkage, see Figure 6.5). The dimensions of the elements could be smaller, reducing the visibility of the fort, an important strategic property (Scharroo, 1909a).

The problems originating in the secrecy of the patent holder can be seen in the design phase of the Hofplein railway viaduct in Rotterdam at the end of the 19th century (see Figure 2.8, for details see Section 8.6). A design and tender was made by a Hennebique office, yet no calculations were handed out to the client, the Dutch railway company *Zuid-Hollandsche Electricche Spoorweg-Maatschappij* (Z.H.E.S.M., "South Holland Electric Railway Company"). The Z.H.E.S.M. had doubts and wanted a verification of the design. Van Hemert was asked to evaluate the design and calculations. His advice was negative due to both theoretical and practical concerns regarding Hennebique's design. However, Van Hemert did not exclude the possibility of successful design in reinforced concrete and was commissioned to design and calculate the viaduct himself. A practical obstacle was that neither generally accepted theories on the calculation of reinforced concrete nor codes of practice existed yet (see Section 2.2.1). Additionally, no reliable material values were available for calculation. Therefore, Van Hemert carried out material tests to obtain reference values of the concrete prior to calculating the viaduct.

The viaduct was constructed between 1904 and 1908, and with the increased experience gained during construction, the design and the type of reinforcement system was adapted (Van Hemert, 1901, 1908). Braak (1907), working as an engin-

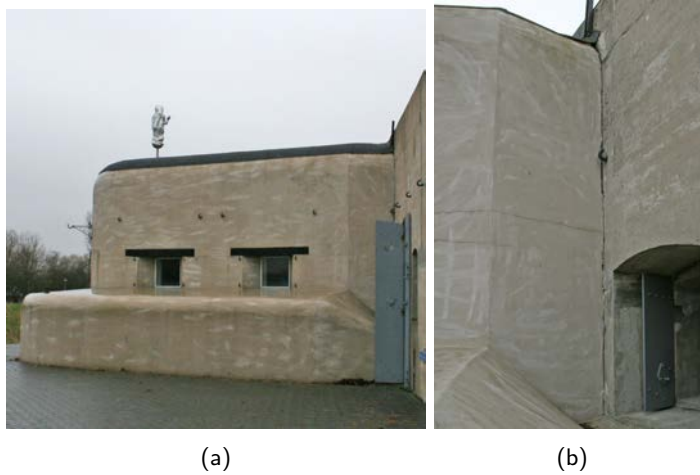


Figure 6.5 Example of a crack between two adjacent building elements in a plain concrete structure (Fort near Vijfhuizen, 1899, situation 2007). a) Overview casemate. b) Crack between casemate and main building.

eer on the Hofplein railway viaduct, described it as a “catalogue” of reinforcement systems usable for viaducts. Then, the viaduct was the largest reinforced concrete project in the Netherlands and the use of reinforced concrete started to become more common. Before, the use of reinforced concrete was restricted to “*small niche markets (e.g. water reservoirs, flower pots, water proof cellars)*” and systems and patents dominated the market, making it difficult for outsiders and customers to understand the material and its calculation (Deuten, 2003).

However, doubts about using reinforcement at all still existed at the beginning of the 20th century; it was feared that the reinforcement would corrode in the concrete. Whereas some stated that the concrete would protect the reinforcement, others said that the combination of concrete and reinforcement was the cause for corrosion (see Section 6.5 *Concrete cover of the reinforcement*). A well-known discussion on the topic whether reinforced concrete is a reliable building material was held between the previously mentioned Van Hemert and the military engineer Pieter Augustus Marinus Hackstroh (1864-1942) in the Dutch journal *De Ingenieur* in 1902 (Hackstroh, 1902a,b; Van Hemert, 1902a,b,c). A review of their discussion of different theories is outside of the scope of this thesis, yet what is relevant is their different ideas about the durability of reinforced concrete.

Hackstroh’s concern was that the then current practice and used theories could lead to cracking of the concrete, and that even hair-line cracks which do not reach the reinforcement could cause a corrosion of the reinforcement. He criticised the current lack of knowledge concerning the method of calculation, the chosen elastic modulus of reinforced concrete and the assumed tensile strength. Additionally, he observed in practice the position of the reinforcement was not always as designed,

increasing the risk of cracking. A main part of their dispute over the reliability of reinforced concrete addressed the theories of calculating concrete. Van Hemert as a former professor for mechanics, defended the current practice of calculation, and even indirectly accused Hackstroh of a member of an older generation which was still used to the concept of plain concrete structures and of iron structures, but had not yet understood the concept of reinforced concrete (Van Hemert, 1902a).

Van Hemert evaluated possible threats caused by cracking from a mechanical point of view, and came to the conclusions that they are not necessarily a statical problem, and cracks did not inevitably lead to corrosion. In fact, he excluded a threat of corrosion as even if cracks would appear, reinforced concrete structures would be regularly inspected and maintained and thereby any serious threat caused by corrosion prevented. Van Hemert was not alone with the ideas that cracks would not lead to corrosion; for example, in a German discussion about Hackstroh's idea, the same response was given and even stated that cracks would never lead to corrosion if the concrete cover is 3.5 cm thick, and tests showed that even if the reinforcement would be visible after cracking, no serious degree of corrosion could be found (Kunse, 1919). Yet, occasional doubts and discussion could not prevent the rise of reinforced concrete. Increasing signs of durability problems such as corrosion did not lead to investigation and adaptations of design rules until the middle of the 20th century.

6.2.1 Terminology of reinforced concrete

The obsolete terminology used for reinforced concrete was initially inhomogeneous and partially differed from modern terminology. Early Dutch terminology for reinforced concrete was mainly influenced by the names used for different proprietary systems. In practice, the two main reinforcement systems, Monier's and Hennebique's, influenced the terminology the strongest. Monier's *ferre-ciment* was translated as the Dutch *cement-ijzer* (literally "cement-iron"); Hennebique's *beton armé* as *gewapend beton* (reinforced concrete). The naming of early reinforced concrete companies reflects the parallel existence of different terms. The term *cement-* or *betonijzer* was used for example by the *Amsterdamsche Fabriek van Cement-ijzer werken, System Monier*; the *Koninklijke Rotterdamsche Betonijzer-Maatschappij v/h van Waning & Co.*, and the *Nederlandsche Maatschappij voor Monierwerken De Amstel*. Other companies used the term *gewapend beton*: *Hollandsche Maatschappij voor Gewapend Beton, N.V. Internationale Gewapendbeton-Bouw Breda* (Figures 6.6 to 6.8). The name choice could be directly influenced by the reinforcement system used, or, especially for companies using the term *gewapend beton*, refer to the official terminology introduced with the G.B.V. 1912, *Gewapend Betonvoorschriften* (G.B.V., Netherlands Code of Practice for Reinforced Concrete).

Even amongst experts the term varied. For example, the draft of the G.B.V. from 1909 used the term *betonijzer* ("concrete iron"). In this draft, *betonijzer* was defined as a composite of *cementbeton* ("cement concrete") and *ijzer* (iron) (Konink-



Figure 6.6 Advertisement for Dutch reinforced concrete construction companies, reflecting the parallel existence of the terms *cementijzer* and *gewapend beton*, and indicating the use a *Monier* and/or *Hennebique* system (Bergsma & Homan van der Heide, 1910a,b).



Figure 6.7 Advertisement for the *Hollandsche Maatschappij voor Gewapend Beton* (Boon, 1908).



Figure 6.8 Former headquarters of the *Koninklijke Rotterdamsche Betonijzermaatschappij v/h van Waning* (Rotterdam, J. I. van Waning, 1898, situation 2010)

lijk Instituut van Ingenieurs, 1909). The term *betonijzer* was influenced by the German term *Eisenbeton*, which was the chosen term in the 1907 Prussian Code (see for example Foerster et al., 1908; Memmler et al., 1907; Deutscher Verband deutscher Architekten- und Ingenieurvereine and Beton-Verein., 1904). Yet, not the term *betonijzer* but *gewapend beton* (reinforced concrete) was used with the same definition in the first edition of the G.B.V. 1912. A different definition of the terms *betonijzer* and *gewapend beton* was made by Scharroo (1910b): *gewapend beton* was defined as a construction where the reinforcement carries the tensile stresses and the concrete the compressive load, whereas *betonijzer* or *cementijzer* was defined as a construction which had a load-bearing framework of *ijzer* (iron) which was embedded in concrete in the case of *betonijzer*, or in cement and *grindzand* (a natural mix of sand and smaller coarse aggregates) in case of *cementijzer*.

The title of early concrete textbooks and publications varied as well. Boon (1908, 1913, 1920, 1931), van Rossum (1902), Scharroo (1910a,b, 1916, 1921), Bergsma & Homan van der Heide (1910a,b) and Dwars (1923) used *gewapend beton*; Sanders (1907) used *cement-ijzer*, Rutgers (1909) and Dwars (1912) used *betonijzer*. From the 1920s onwards, a more homogenous terminology was applied, and in general the term *gewapend beton* was used for reinforced concrete. In this period, the transition from proprietary systems to a generally available concrete technology had been achieved, and therefore the systems influenced less the terminology for reinforced concrete.

6.2.2 Terminology and composition of the used metals

Nowadays, steel is the most commonly material used for reinforcement and the bars have, in most cases, a circular cross-section (NEN-EN 10080:2005). For the reinforcement of historic concrete, the used ferrous metals varied during time, both in terminology, classification and material properties; a direct translation into modern terminology is not always possible. The differences between the obsolete Dutch and English terminology are significant: for example, the English term steel was applied earlier and covers some ferrous metals which would have been considered in Dutch as *ijzer* (iron). Tilly & Jacobs (2002) define for the British situation historic steel as “*basically iron with carbon (with typically 2% maximum of weight) and other elements added*”. Only with the introduction of multi-lingual European standards in 1973 the terminology between English and Dutch became comparable. Therefore, in this thesis, after an explanation of the terms in the following sections, reference will be made to the original Dutch terminology. In Appendix A, an overview is given of obsolete translations (English, Dutch and German) of the different iron and steel types used, showing already inconsistency in contemporary translations.

The slight but possible meaningful differences between national terminologies concerning iron and steel are not often considered in the mainly English academic publications. Confusion can occur due to incorrect translations (in particular

between English -current lingua franca- and other languages), as for example the historic differentiation between iron and steel varied in different countries, and no definition of the term steel is given in the context of the case study and national historical terminology. In published case studies, a material characterisation of the different iron and steel types is not mentioned and too often the term steel is used for all types of reinforcement (for example Bertolini et al., 2008; Mezzina et al., 2010). A clarification of the term steel is not given, if it is defined by its metallurgical composition (for example carbon content), production method or if the term was used due to unawareness of the historical differences in ferrous metals used for reinforcement

A sound differentiation and identification of the used metals can be relevant for conservation, as the different metallurgical variables can influence the corrosion rate of the used *ijzer* and *staal*. Their different corrosion behaviour was still discussed in historic publications, dating back to the period when both metals were applied for construction (for example Cleary & Greene, 1967; Sang, 1910). More recent publications on corrosion and on reinforcement corrosion, however, address only modern steel types (for example Broomfield, 2007; Shreir, Jarman & Burstein, 1994); even publications on the conservation of historic concrete neither address the metallurgical differences of iron and steel nor its influence on the corrosion (Macdonald, 2003; Sutherland et al., 2001). From steel/iron structures it is known that “*steel corrodes more readily than either cast or wrought iron*” and that the properties can be poorer and “*that structural steel produced before 1955 was of much poorer quality than present day mild steel. [...] Also, steel produced by the Bessemer or open hearth processes which were used up to the 1970s tended to be more brittle because it contained more nitrogen from the blast*” (Tilly & Jacobs, 2002). Another general information is that rate of corrosion depends on the purity of the metal, and the purer the metal, the better the corrosion resistance. The corrosion behaviour of the different metals can differ as well, from *vloeiijzer* (ingot iron) used in iron structures it is known that it starts locally and spreads slowly (Van Maarschalkerwaart, Oosterhoff & Arends, 1997). Detailed information and fundamental research of the properties and corrosion behaviour of historic ferrous metal reinforcement is still missing. Publishing of more data of the properties and corrosion behaviour of historic reinforcement is considered necessary (see also Bertolini et al., 2011).

A better understanding and prediction of the corrosion rate and remaining service life of the reinforcement in historic concrete can be relevant when crucial decisions have to be made whether historic reinforcement has to be removed or its presence in-situ can be prolonged. For electrochemical treatments which intend to slow down the corrosion rate (see Section 9.4.5), such information can be relevant as well. Yet this requires a better understanding of the metallurgical composition and of the influence of the iron phases, knowledge which is currently not available. More common situations such as adding or replacing new metal elements next to the historic reinforcement require attention to the original metal as well, as some metal combinations can cause galvanic corrosion. In such a case the less noble

metal would corrode due to electrochemical process between the two metals. As less noble metals, compared to modern alloys steels and stainless steel, were used as reinforcement, especially at the turn of the 19th century, it has to be evaluated whether this can be a practical or only a theoretical problem. The metallurgical composition influences the weldability as well, and, as De Bouw (2010) criticises, the modern thresholds to evaluate the weldability, such as the carbon content, the sum of the phosphorus and sulphur, and nickel content, cannot be simply applied to historic iron as some irons which would have been unweldable according to these criteria proved to be weldable; however further research is still required.

In the late 19th century, when reinforced concrete faced its first wide scale application, the steel and iron industry was characterised by significant innovations in production, such as new types of furnaces.¹ As neither unified terminology nor standards existed, the terms for iron and steel could vary depending on the production method (e.g. type of converter), material properties, and due to local traditions. De Bouw (2010) showed for the Belgian situation the former and present confusion when it comes to distinguish historic steel and iron terminology. Historic literature already addressed the different terminologies, and awareness existed that a direct translation was not always possible. In French and English terminology, steel referred to all irons which were forgeable, produced by melting, which could therefore also refer to iron types with a low carbon content and thereby supporting the confusion between steel and iron (Memmler et al., 1907).

Besides the confusion of translating the terms for iron and steel into different languages, there was also confusion within the Dutch language. From the 1920s onwards, when the distinction between *staal* (steel) and *ijzer* (iron) became more explicit, the term *ijzer* was still used commonly instead of the term *staal*. For example *smeedbaar ijzer* (forgeable iron) could refer to both, *ijzer* and *staal*; the maximum carbon content to be *smeedbaar* (forgeable) was considered to be 1.5% (Landberg, 1919). As no clear line between *vloeiijzer* (ingot iron) and *staal* could be drawn, sometimes the strength of the metal was used as criterion, and

¹The following four types of furnaces were the most relevant for the production of *ijzer* and *staal* used for reinforced concrete. The basic Bessemer converter revolutionised and increased the iron and steel production in the second half of the 19th century. Prior to the invention of the Bessemer converter (1855 first patent), the main production method was puddling, where air was introduced into the molten pig iron by stirring or puddling rods in the melted pig iron. In the Bessemer converter, the air was blown directly through the molten pig iron, which resulted in a purer end product and lower carbon content. The idea behind blowing air through the molten iron is to reduce the impurities, and is also known as oxidation. However, the resulting *ijzer/staal* had a high phosphorus content. An improvement towards the Bessemer converter was the basic Gilchrist Thomas converter, which was in principle similar to the Bessemer converter but the phosphorus content was reduced as CaO was added to the pig iron in the converter and the molten iron was blown longer. The basic Siemens-Martin open hearth was based on a different principle where preheated air and combustible gases were blown over the molten iron in an open hearth. Its advantage was that also scrap iron could be used as raw material. The electric furnace appeared at the beginning of the 20th century, and allowed the production of rather pure steel and of alloys. However, an economic use depended on the availability of low-priced electricity (Van der Kloes, 1908b). For further details on the production of historic iron and steel, see De Bouw (2010) and Van Maarschalkerwaart et al. (1997).

with a tensile strength above 50 kg/mm² called *staal* (Van der Kloes et al., 1925).

The changes in terminology from *smeedbaar*- or *vloeiijzer* to *staal* became necessary as it was difficult to draw an exact line for the definition of the two materials (Van der Schrier, 1938). The terminology changed officially with the introduction of standards at the beginning of the 1930s. Even after the official Dutch definition of *staal*, which included most ferrous metals used for construction, the term *ijzer* was still commonly applied up to the 1940s (Oosterhoff, 1998).

Despite the confusion encountered in Dutch practice, three main ferrous metals used for reinforcement can be identified, and will be discussed in the following paragraphs: *welijzer* (wrought iron), *vloei*- or *smeltijzer* (ingot iron), and (*vloei*-) *staal* (steel) (see Table 6.1 and Table 6.2). Their definition is not always consistent in modern references and their chemical composition seldom discussed. As the ferrous metals used for the reinforcement are seldom characterised during conservation projects or historical investigations, little is known about their composition in detail and also not discussed in reinforced concrete textbooks. In one of the few reference works for historic iron structures in the Netherlands (Oosterhoff et al., 1988), the classification of *ijzer* and *staal* is based on the production method, yet it neither mentions *vloeiijzer* nor *smeltijzer*, which were the official terms for the main iron type used at the beginning of the 20th century. In the latest reference work for historic materials used in the Netherlands (Bot, 2009), only *smeltijzer* is mentioned and not its synonym *vloeiijzer*, which became the official term after 1911. The late 19th and early 20th century, however, is a period of major changes in the production and quality of iron and steel, and should be considered during the conservation of historic reinforced concrete, both technically and in terms of construction history.

Welijzer (weld iron (Van der Kloes et al., 1925), wrought iron (Koninklijk Instituut van Ingenieurs, 1911)) was produced by puddling and was malleable (Memmler et al., 1907; Van der Kloes, 1908b). In general, *welijzer* was mainly used for structural elements between 1860 and 1900, seldom after 1900 (Van Maarschalkerwaard, 1996). Its use as reinforcement for concrete was limited as it was difficult to obtain and had a low strength (Boon, 1920; Van der Schrier, 1938). Additionally, *welijzer* was only allowed for secondary reinforcement elements according to the G.B.V 1912, resp. 1918. Rivets and bolts, used as connections for rigid reinforcement systems, were one of the possible uses of *welijzer* in historic concrete. It is characterised by a low carbon content (circa 0.04%) and a relatively high phosphor content (circa 0.50%) (Van Maarschalkerwaard et al., 1997).

Smeltijzer and ***vloeiijzer*** (Ingot iron (De Bouw & Wouters, 2008; Van der Kloes, 1908b; Van der Kloes et al., 1925), steel (Koninklijk Instituut van Ingenieurs, 1911)) were often used as synonyms, with earlier reference works using *smeltijzer* (compare Boon, 1908, 1913). The 1900 edition of the *Algemeene Voorschriften IJzer* (A.V.IJ. Code of Practice for Iron) preferred the term *smeltijzer* (“molten iron”) as it reflected better the production method than *vloeiijzer* (“flowing iron”). However, with the A.V.IJ. 1911, the terminology changed officially to *vloeiijzer* (Koninklijk Instituut van Ingenieurs, 1911). In practice, the term

Table 6.1 Overview of the irons and steel allowed in the different editions of the G.B.V.

	Vloeijsier (in- got iron)	Weljsier (weld iron)	Staal (Steel)	Betonstaal (rein- forcing steel)	Profielstaal (sec- tion steel)
Concept G.B.V. 1909 art. 6	✓	(✓), max. 8 mm thick			
G.B.V. 1912 art. 6 IJzer	✓	(✓), max. 6 mm thick			
G.B.V. 1918 art. 6 IJzer	✓	(✓), max. 6 mm thick			
G.B.V. 1930 art. 9 IJzer	✓ (only one al- lowed)	-	✓ (in 4 th edition) min. com- mercial quality		
G.B.V 1940 art. 9 Staal	-	-	✓ (as only one) min. commer- cial quality		
G.B.V. 1950 art. 9 Staal	-	-	✓ QR22; Commercial quality not allowed	Commercial qual- ity not allowed	
G.B.V. 1962 art. 17 Staal			Commercial quality not al- lowed	✓ according to V1035-4	✓ according to V1035-4

Note: V 1035:1941 Keuringsvoorschriften voor metalen - IJzer en staal (Standard for the testing of metals) ; V 1035-IV:1952 Ontwerp Keuringsnormen voor metalen . Constructiestaal.
Legend: ✓ Allowed; (✓) Restricted use allowed.

Table 6.2 Overview of types of iron and steel advised for reinforcement in Dutch literature.

	<i>Ijzer</i> Iron	<i>Vloeiijzer</i> ingot iron	<i>Smeltijzer</i> ingot iron	<i>Welijzer</i> weld iron	<i>Staal</i> Steel	<i>Vloeistaal</i> weld steel	<i>Betonstaal</i> reinforcing steel
1900 - 1930s	Van Hemert, 1901	++		+	-		
	Van Rossum, 1902		+	+/-			
	Boon, 1908		+	+	\$		
	Van der Kloes, 1908b; Van der Kloes et al, 1924	+					
	Bergsma et al, ca. 1910a		+	-	+\$		
	Scharroo, 1910a, 1916		+	- †	- †		
	Verhey, 1912	+					
	Boon, 1913		++	+	+\$		
	Boon, 1920; Scharroo, 1921		++		+\$		
1930s-1960s	Boon, 1931		++		+\$		
	Bergsma, 1934		++ ⁽¹⁾				
	Van der Schrier, 1938, 1942		++/+ ⁽²⁾	-			
	Scharroo, 1940, 1942a				+		
	Van der Schrier, 1949, 1951, 1953, 1960					+	
	Van der Schrier, 1957, 1968						+

Legend: ++ main advice; + positive; -negative; \$ expensive ; †seldom used.
Footnote: ⁽¹⁾ St.37; ⁽²⁾ ++ by St.37, + by St. 32 (Steel class).

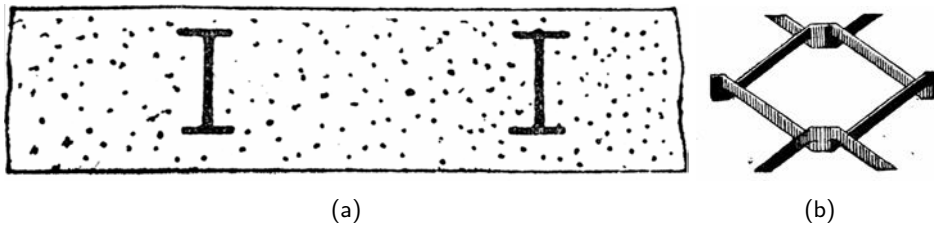


Figure 6.9 Illustrative drawings of reinforcement types (van Rossum, 1902, page 107).
a) Standard double-T sections. b) Expanded metal.

vloeiijzer was already used before 1911 (see for example Braak, 1907).

In the A.V.IJ. 1911, it is defined as an *ijzer* which was made in the converter or with the open hearth process. *Vloeiijzer* was then the main produced iron for construction works, which supported its use as reinforcement (Memmler et al., 1907). It was initially preferred as reinforcement, as *welijzer*, with similar costs, had a too low strength and *staal* was too expensive (Boon, 1908, 1913, 1920; Scharroo, 1910a; van Rossum, 1902). In the G.B.V. 1912, as well as in the G.B.V. 1918, *vloeiijzer* and *vloeistaal* were mentioned as the main reinforcement materials. In the G.B.V. 1930, only *vloeiijzer* was allowed, and in the G.B.V. 1930 the terminology changed from *ijzer* to *staal* (see Table 6.1). Besides plain round reinforcement bars, other possible shapes made with *vloeiijzer* were profiled cross-sections, standard iron sections and expended metal (see Figure 6.9 and Christophe, 1905).

Based on the experience gained from iron bridge constructions, *vloeiijzer* produced in the Siemens-Martin process was preferred in the Netherlands. An example dating from 1900 is the former railway bridge over the *IJssel* near *Westervoort*, which was destroyed during the Second World War (Van Maarschalkerwaart et al., 1997). *Thomas-vloeiijzer* was too inhomogeneous and in the 1920s, it was discovered that its properties decreased during time due to the high nitrogen content based on the production in the converter (Brandes, 2008; Van Maarschalkerwaart et al., 1997). The properties of *vloeiijzer* could vary strongly, depending on the production method and used raw materials, and it had a low carbon content (for example 0.16% is mentioned in Van der Kloes et al., 1925).

An example for the reasoning to choose *vloeiijzer* is documented in Van Hemert's description of the calculation of the Hofplein railway viaduct. Van Hemert chose *vloeiijzer*, as it was already commonly applied for bridge constructions and had a similar price as *welijzer* (weld iron). The elasticity of *vloeiijzer* was 23-25 kg/mm², twice the elasticity of *welijzer*. *Vloeistaal* (weld or Ingot steel) could not be used as Van Hemert wanted to apply profiled reinforcement elements, which were not available in *vloeistaal* (Van Hemert, 1901).

The definition of *staal* (weld steel or Ingot steel, see Van der Kloes, 1908b; Van der Kloes et al., 1925) varied during time, depending either on the production method or on the carbon content. Sometimes the synonyms *vloeistaal* and *smeltstaal* (Van der Kloes, 1908b; Van der Kloes et al., 1925; Van Hemert, 1901)

were used. The initial criterion to distinguish between *ijzer* (iron) and *staal* (steel) was the hardenability of the metal; if cooled rapidly after heating to high temperatures, causing a higher hardness, it was called *staal* (Van der Kloes, 1908b). Later introduced distinguishing features were the carbon content and the property of being malleable materials (see for example Landberg, 1919). As *staal* was expensive, it was initially only advised as reinforcement when the dimensions of the bars had to be reduced (Boon, 1908, 1920). An occasional objection against the use of *staal* was that it could be too brittle (Scharroo, 1921, 1942a). Contrary to other countries such as Austria and Germany, mild steel was commonly used in the Netherlands (Gantvoort, 1964).

After the First World War, the influence of the carbon content on the quality and the chemical composition is discussed more in detail (see for example Landberg, 1919; Vosmaer, 1922). The carbon content influenced the hardenability; below 0.5% the hardenability was little (Vosmaer, 1922). The threshold for the carbon content varied during time: 2.6% (Van der Kloes, 1908b; Van der Kloes et al., 1925), 1.7% (van Dam, 1948; Van der Kloes, 1908b; Van der Kloes et al., 1925), whereas in practice the carbon content of *handelsstaal* (commercial steel) did not exceed 1.2% (Vosmaer, 1922). In the same period in Germany, an official differentiation between iron (German *Eisen*) and steel (German *Stahl*) based on the carbon content was already applied, where the threshold for steel was a minimum carbon content of 0.5% (Memmler et al., 1907). For the United States of America the threshold for steel was a carbon content above 0.04%, if it was below 0.15% it was called a mild steel, but also here it was admitted that the demarcation was mainly based on physical properties due to the manufacturing and less on the chemical properties (Sang, 1910). The dividing line between steel and cast-iron is nowadays made at 2% content of carbon and other elements (NEN-EN 10020:2000).

The influence of the metallurgical composition on the corrosion of the iron and steel was already discussed at the beginning of the 20th century, as well as which alloys and impurities could be beneficial and which detrimental with respect to corrosion (Sang, 1910). Nickel and chromium were considered beneficial, and a high chromium content became the main characteristic of stainless steel. Phosphorus and silicon alloys were discussed whether they were beneficial or not, manganese and sulphur were considered to be of a negative influence. Later publications agreed on the detrimental properties of carbon and phosphorus, and that especially a carbon content between 0.5% and 0.7% could increase the corrosion rate (Cleary & Greene, 1967).

6.2.3 Quality and classification of the used ferrous metals.

Reinforcing steel is nowadays classified according to its mechanical properties such as its yield strength, and is designated with the letter *S* followed by a numerical indication of the mechanical property, the yield strength in N/mm², for example S235 (NEN-EN 10027-1:2005; NEN-EN 10080:2005; NEN 6008:2008). The main

material used is steel, and the use of iron is not discussed anymore for reinforced concrete.

When reinforced concrete was introduced in the Netherlands in the late 19th century, the differentiation between *ijzer* (iron) and *staal* (steel) was part of the classification. In the preface of the 1900 edition of the *Algemeene Voorschriften IJzer A.V.IJ.* 1900 (Code of Practice for Iron), it was explained that the term *staal* was only used to distinguish between *gegoten ijzer* (cast iron) and *gegoten staal* (cast steel), all other types were called *ijzer*. In the A.V.IJ. 1900, *ijzer* was classified according to the production method followed by numerical classification I - VI for the shape, and letter as a quality indicator a-d; for example *Smeltijzer IIIa*. In practice, reference was also made to the use of *vloeiijzer* according to the A.V.IJ. for the reinforcement (for example Braak, 1907).

In the following edition of the A.V.IJ. from 1911, the classification and partially the terminology changed; *vloeiijzer* (ingot iron) replaced *smeltijzer*, *staal* was now a synonym for *vloeiijzer*. *IJzer* was still classified by the production method, for example *vloeiijzer*, and by the quality, but the naming of the classes changed. The quality was now expressed in three classes, 1-3, and further distinguished by the letters A - E, where A1 would represent the highest quality. According to the G.B.V. 1918 and the A.V.IJ. 1911, a usable reinforcing *ijzer* (iron) would have been a *vloeiijzer*, either in the classes A1 or B1. The G.B.V. 1912, which did not refer to the A.V.IJ., required a higher class of *vloeiijzer*, with a minimum tensile strength of 37 kN/mm², which would exclude the use of *vloeiijzer* B1.

In 1932, the first Dutch standard for *staal* (steel) was published, the N 702:1932 *Staal (gewalst of gesmeed) soorten en beproevingseischen* (Steel (rolled or forged) types and testing criteria), and four classes are introduced:

St.00 also known as *staal in handelskwaliteit* (commercial quality steel). No testing was required besides its appearance and weight.

St.# with a numerical character which indicated the minimum ultimate tensile strength (*breukgrens* or *trekvastheid*); for example St.37 for *staal* with an ultimate tensile strength of 37 kg/mm²

St.A# with a numerical character which indicated the minimum ultimate tensile strength; additionally the *staal* has to fulfil a certain, not further defined, chemical composition and a minimum yield strength.

St.C# with a numerical character; it has to fulfil the same requirements as St.A. but additionally a certain carbon content is required. The numerical character does not indicate the strength but the carbon content in %.

The main changes in the second edition from 1934 (N 702:1934) was that the class St.C. was not mentioned anymore and a classification according to the production method was introduced, with Th = *Thomas staal*; B = *Bessemer staal*, M = *Martinstaal*; E = *Electrostaal*. Steel was divided in two groups, group I referring to rolled steel, including steel for construction, and group II to rolled or forged steel such as used for toolmaking. The different classes according to the

tensile strength were St.00; St.34 and St.A34; St.37 and St.A37; St.41 and St.A41; St.44 and St.A.44; St.50 and St.A.50; St.60 and St.A.60, St.70 and St.A70. St.37 was mentioned as *betonstaal* (reinforcing steel). An example for the naming would be the following: N702 St.37 - I - B - Om; whereas the last letter combination would indicated the method of testing, for example Om referring to mechanical testing. The use of all indicators was not necessary if they were not relevant.

For the first, the chemical composition was addressed. Maximum contents (in mass percentage) of phosphor (between 0.07 and 0.085), sulphur (between 0.07 and 0.085), and of the combination of phosphor and sulphur (between 0.12 and 0.15) were given. In the N 702:1934, the maximum content was differentiated according to the production method, with the two groups *Bessemer-* and *Thomas-staal* and *Martin-* and *Electro-staal*, where for the latter group lower values were required, values which lay up to 50% above the present day limits of the NEN 6008:2008. For comparison, the present day maximum content (in mass percentage) of carbon C is 0.22, sulphur S 0.050, phosphorus P 0.050; additionally limits are given for nitrogen N 0.012 and copper Cu 0.80 (NEN 6008:2008). A carbon content was not mentioned in the N 702:1934, but it is known that a St.48 had a carbon content of 0.25 – 0.30%, a St.52 of 0.17 – 0.25% and chromium, copper and manganese were added as alloys (Van Maarschalkerwaart et al., 1997).

For building construction, the most commonly used classes were St.34 and St.37 (Scharroo, 1942b; Van der Schrier, 1938). Due to the indifference in terminology in practice between *ijzer* and *staal*, a St. 37 was also called *handelsvloeiijzer* (commercial ingot iron) or *staal* with *handelskwaliteit* (commercial quality) (Bergsma, 1934; Boon, 1931). This terminology contradicts the terminology used in the standard N702, where a *staal* in *handelskwaliteit* was defined as a St.00. In the G.B.V. 1950, *staal* in *handelskwaliteit* was not allowed anymore to be used as reinforcement. In the period when the terms *staal* and *ijzer* were used in parallel and even confounded in practice, St.48, resp. St.52, was considered as *staal* (steel), whereas lower classes were called *ijzer* (iron).

St.37 was the commonly advised quality for reinforcement. The higher quality St.48 was advised when the cross-section of the reinforcement needed to be reduced and often used in combination with high quality cements, such as early high strength or rapid hardening cements (see Section 3.6.2) (Van der Schrier, 1938, 1942). The use of a smaller cross-section could be beneficial for the construction of slender concrete members such as columns as the fresh concrete could be poured and compacted better. Later, St.48 was in practice replaced with St.52. To avoid the accidental use of bars with the wrong quality, a mark was rolled on St.52 (Gantvoort, 1964). During and shortly after the Second World War, the use of high quality *staal* increased in the time of material scarcity as it could carry higher stresses than normal St.37 and thereby less material was needed (Bergsma, 1934). However, as the high quality was due to its chemical composition it was too expensive for most cases, and cold-worked steel (see Section 6.3.4) was used instead (Scharroo, 1946; Welling, 1953). In the 1950s, the use of high quality *staal* was discussed more due to the increasing interest in pre-stressed concrete.

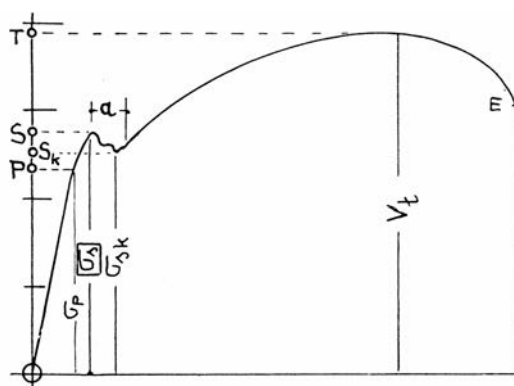


Figure 6.10 Stress-strain diagram for steel with the stress σ at the abscissa and strain at the ordinate. The point V_t indicates ultimate tensile strength and σ_s the yield strength (Bergsma, 1934, p. 44).

At the beginning of the 1950s, the classification for steel changed once again. The main difference was that the yield strength σ was now used as a reference for the steel quality and not anymore the ultimate tensile strength. The concept of using the yield strength instead of the ultimate tensile strength to indicate steel quality was not new and already considered at the beginning of the 20th century (for example Memmler et al., 1907). The yield strength was considered as a more relevant value as it indicates the point when the steel would deform plastically, and not fail as used to determine the tensile strength (see Figure 6.10).

Besides the reference for strength, the letters to indicate the quality changed as well. The quality classes were now H and Q instead of St. *Staal* or *normale handelskwaliteit* (normal commercial quality) was designated as H; *staal* of special quality as Q, which included requirements towards the mechanical properties and structure. If chemical requirements had to be met as well the *staal* was designated Qc. The Q could be followed by the letter R and a numerical character, indicating the yield strength; the letter n indicated that the *staal* was cold-worked (see V 1035-IV:1952, Van der Schrier, 1951). For example a QR22 had a minimum yield strength σ of 22 kN/cm². For comparison, the previously used St. 37 had a yield strength between 24 and 26 kN/cm² (Van der Schrier, 1938). The normal qualities used for reinforcement were QR22 and QR24; and as high quality QR32, QR40, QR48, QRn32, QRn40 and QRn 48 (G.B.V. 1962). QR 24 became the most common type, QR 22 and QR 32 were seldom used, QRn 48 was used for welded wire meshes (Gantvoort, 1964).

In the pre-standard V 1035-IV:1952 *Ontwerp Keuringsnormen voor metalen - Constructiestaal*, the classification of reinforcement steel was compared to the classification used in German, British, and Belgian standards. Dutch *staal* of a quality below QR42 would have been comparable to mild steel according to British standard BS 785:1938, a QR42 to medium tensile steel, and QRn48 and QRn54

to high tensile steel. Compared to German standard DIN 1045:1943 paragraph 6, Dutch QR22 would be comparable to *Betonstahl I*, QR42 and QRn48 to *Betonstahl IIa*. The Belgian standard *NBN 179-1949* consisted of only two classes, A00 and A37, where A37 would be comparable to QR24.

With the founding of the European Coal and Steel Community in 1953, unification and harmonisation of terminology and properties of steel in different languages by means of European standards, the EURONORMs, was introduced. EURONORMs “*fix[ed] the general rules of conventional designation of steels by means of alphabetical and numerical symbols representing certain basic characteristics*” (Commission des Communautés Européennes, 1974). With the entry of the United Kingdom into the European Economic Community in 1973, unification of terminology and classification included English as well. English steel and Dutch *staal* both now referred to “*ferrous products which are generally suitable for hot shaping. With the exception of certain steels with a high chromium content, they contain less than 1,9% carbon*” (Commission des Communautés Européennes, 1974). The classification was an alphabetical symbol, Fe, followed by a numerical symbol for the guaranteed minimum tensile strength in kgf/mm², for example Fe42 (Commission des Communautés Européennes, 1974). The Fe classification was already introduced with EURONORM 27 in 1962, but in practice the classification QR according to Dutch standards was used.² More recent are the classification using the letters Fe, followed by B, indicating that it is reinforcement steel, and numerical indications of the minimal yield point in N/mm², for example FeB 220 (NEN 6008:1991). This classification was replaced by the previously mentioned European classification using the letter S followed by a numerical indication of the mechanical property (NEN-EN 10027-1:2005; NEN-EN 10080:2005; NEN 6008:2008).

6.3 Geometry of reinforcement bars

The geometry of reinforcement bars is defined by the cross-section and the texture of the bars. Besides plain reinforcing bars, profiled, meaning either a special texture or cross-section, reinforcement bars were used for Dutch historic concrete. A wide variety of reinforcement bars existed at the beginning of the 20th century, although in the Netherlands mainly plain round reinforcing bars were applied. Early proprietary reinforcement systems used mainly normal profiles: Monier used plain circular bars (Section 6.3.1), Hennebique a combination of plain circular bars and flat strips (Section 6.3.2). Yet besides the plain bars, the use of special reinforcement bars with distinct texture and shape was advertised. One motive was commercially as different bars types could be patented (Section 6.3.3). The

²In his review on the standardisation and classification of steel qualities in the Netherlands, Bot (2009) does not mention the “Q” classification introduced in the 1950s; instead, reference is made to the classification introduced by the European Coal and Steel Community in the European standard EURONORM 27-1962, which could exist parallel to the Dutch standard.

other motive was from engineering; by modifying the surface texture and shape, a better mechanical bond between the reinforcement and the concrete was achieved, which was relevant for the mechanical performance (Probst, 1917, 1935). Other approaches were to use commercially available standard iron profiles and to embed them in the concrete or to combine them with a special reinforcement design.

In the first decades of the 20th century the number of reinforcement types reduced due to scientific insight into the behaviour of the reinforcement (e.g. bond, mechanical behaviour), practical experience and decrease of proprietary systems. Two main categories of reinforcement bars crystallised: circular bars and profiles (Burchartz et al., 1927). From the 1920s onwards, special reinforcement bars were developed to either increase the bond or the tensile strength of the reinforcement. The progress in welding technology after the First World War allowed the production of welded-meshes which reduced the amount of labour on the construction site when placing the reinforcement. Welded meshes were introduced in the 1930s in the Netherlands (Section 6.3.6). In this period, another group was introduced: pre-stressed reinforcement bars; it was understood that twisted cold worked bars could carry, with the same cross section as normal bars, higher tensile stresses (Section 6.3.4).

In the Netherlands, some special reinforcement bars were successfully applied prior to the Second World War: welded meshes (*Baustahlgewebe*), cold twisted bars (*Isteg-staal*, *getordeerd-kruisstaal*), bars with elevations (*Nokkenstaal*) or indentations (*Griffelstaal* or *Poolsijzer*), ribbed reinforcement bars (*Torstaal*, *Torwastaal*) and combinations of standard I-profiles with round bars (*Alpha-staal*). These bars became less available during and shortly after the Second World War (Van der Schrier, 1951, 1953). In later publications (Van der Schrier, 1957, 1960, 1968), only different versions of ribbed reinforcement bars (Section 6.3.5) and the *Alpha-staal* are mentioned as special reinforcement bars. This reflects the then common practice where ribbed reinforcement bars and welded wire meshes became the most common profiled reinforcement types.

The geometry of the reinforcement was not explicitly addressed until the G.B.V. 1962, art. 17.2, where for the first reinforcement was distinguished by its shape and texture. It was classified as smooth and profiled, whereas the profiled reinforcement for concrete was classified into the following three groups:

- Non-prismatic bars with a continuous cross-section such as twisted bars with a cross-wise or rectangular cross-section.
- Bars with ribbed surface, including twisted bars.
- Welded wire meshes.

6.3.1 Plain reinforcing bars

Reinforcing steel with a smooth surface texture and a prismatic cross-section is defined as plain reinforcing steel in modern standards (NEN-EN 10080:2005). Bars

with such geometric properties were the most commonly used reinforcement bars for historic concrete in the Netherlands (see Figures 6.11 to 6.13), and in other European countries such as Germany. Common Dutch terms were *staafijzer* (bar-iron) and *betonijzer* (concrete-iron) and were initially available in *welijzer* (weld iron) and *vloeijzer* (ingot iron) (Van der Kloes et al., 1925).

Although it was known that profiled and textured bars achieved a better bond with the concrete, plain round bars were considered as sufficient. To increase the slip resistance of the plain reinforcing bars, their ends were bent up (see Figure 6.14, Boon, 1908; Memmler et al., 1907). Practical advantages such as their easier calculation and placement, and above all being cheaper, supported their application (Dwars, 1923; Scharroo, 1916, 1946; Van der Schrier, 1938, 1942, 1951).

The diameters of the bars were between 6 and 40 mm (Van der Schrier, 1938), resp. 50 mm (Van der Schrier, 1951). Small bars (4 mm diameter) were used as auxiliary reinforcement to secure the position of the main reinforcement during construction (Dwars, 1923). Concerning the diameters of individual bars, a tendency to use more bars with smaller diameter instead of few thick bars can be noticed during time; this had the advantage that while using the same reinforcement percentage more surface area was available to bond with the concrete and the formation of cracks was better distributed.

Round bars were often associated with Monier's system and reference was often made to it when addressing their use (Boon, 1908, 1913; Dwars, 1923; Gantvoort, 1964; Probst, 1917, 1935; Scharroo, 1946). For Monier constructions (see for example Figure 6.11), plain bars were used as main and secondary reinforcement, and for stirrups. With the differentiation of the geometry of the reinforcement bars in the G.B.V. 1962, bars with a smooth surface and circular, oval, and squared cross-sections were classified as *glad betonstaal* (smooth reinforcement bar).

6.3.2 Standard profiles

When the application of reinforced concrete emerged in the Netherlands in the late 19th century, a wide variety of profiles was already available for iron constructions. The profiles were only produced in *vloeijzer* (ingot iron) (Van der Kloes et al., 1925), and usually imported from Germany, Luxembourg, and Belgium (Oosterhoff et al., 1988). For reinforced concrete, the commonly used standard profiles were single T-sections, I-sections and U-sections (Boon, 1908). The profiles had similar dimensions as known from iron construction and were not specially developed for reinforced concrete. Besides being used as reinforcement which was embedded in the concrete (see Figure 6.9), standard profiles were used in combination with plain concrete structures, for example plain concrete floor constructions (see Figure 6.2) or beams above window openings (see Figure 6.15). For military structures, I-sections and railway profiles were used as beams to carry the up to 1.50m thick plain concrete shelter (see Figure 6.16), a construction technique which was abandoned as with the same iron quantity better resistance could be achieved by directly reinforcing the concrete shelters (Scharroo, 1909b).

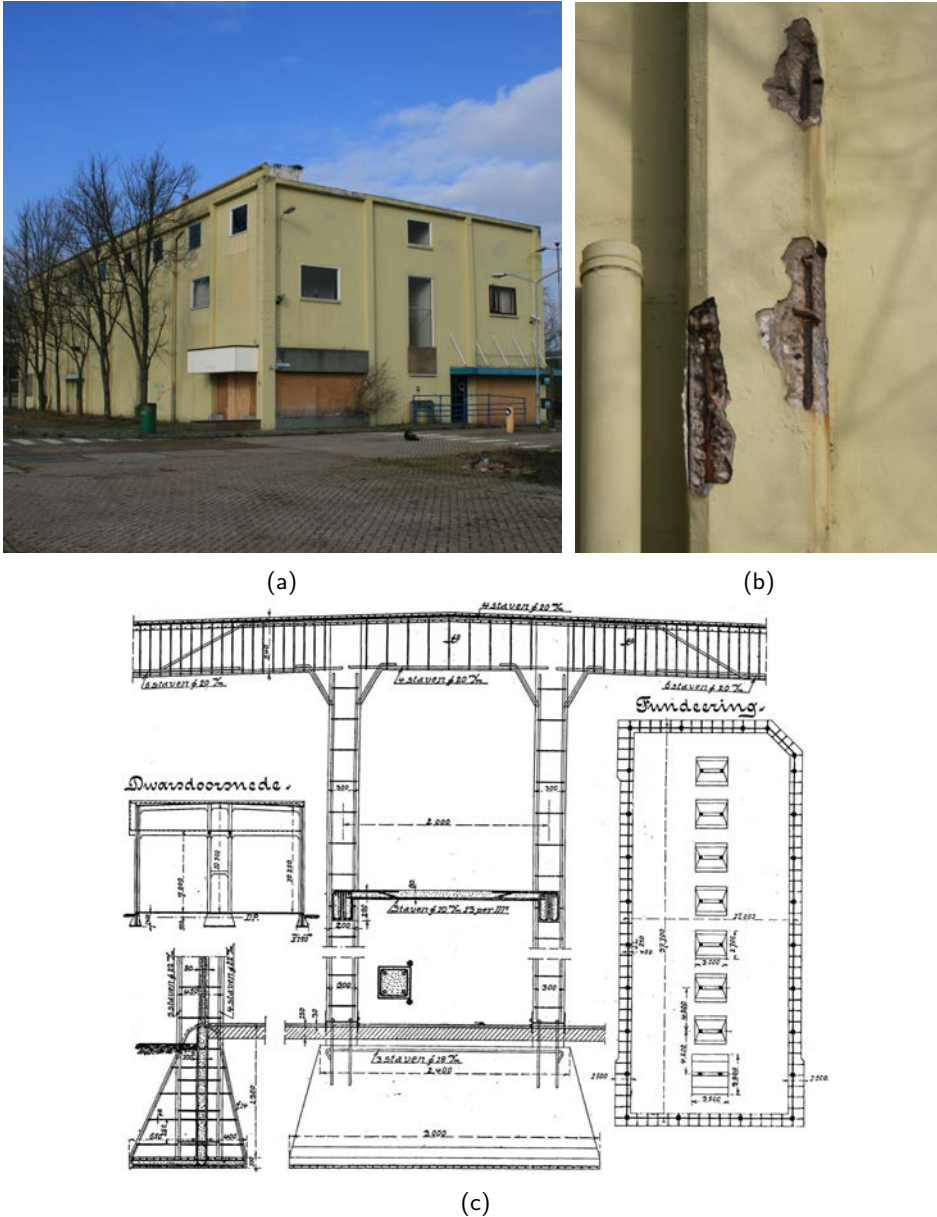


Figure 6.11 Earliest known still remaining Dutch factory building designed according to the Monier system built by *Amsterdamsche Fabrik van Cement-IJzerwerken Wittenburg* (Calvé factory, Delft, 1905, situation 2010) (see also Stenvert & Dekker, 2009). a) Overview. b) Detail of a column, with visible plain reinforcement bars due to spalling. c) Constructions drawing of the reinforcement (Sanders, 1907, p. 334).

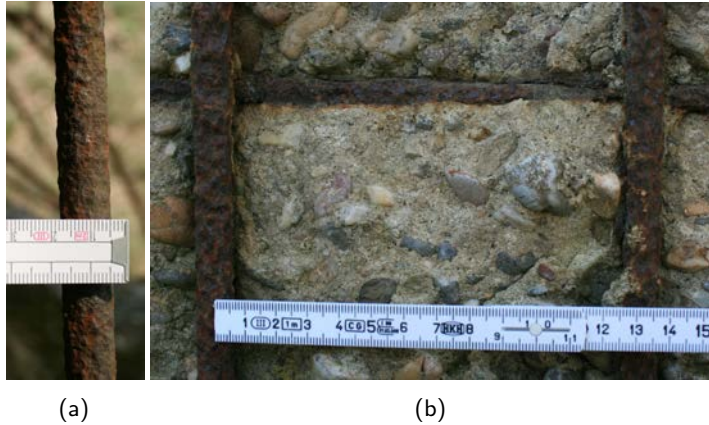


Figure 6.12 Plain circular reinforcement bars (unfinished *Grote Museum, National Park Hoge Veluwe*, H. van de Velde, 1921-1922, situation 2008). a) Single bar, the surface texture is affected due to corrosion. b) Vertical and horizontal bars of a wall, notice the lack of a connection (e.g. wires) between vertical and horizontal bars.



Figure 6.13 Plain circular reinforcement for main reinforcement and stirrups of a beam (Central Station Rotterdam, 1950-1957, S. van Ravesteyn, picture taken during the demolition of the station in 2008).



Figure 6.14 Different examples of bar ends to increase the slip resistance (Boon, 1908, p. 78).

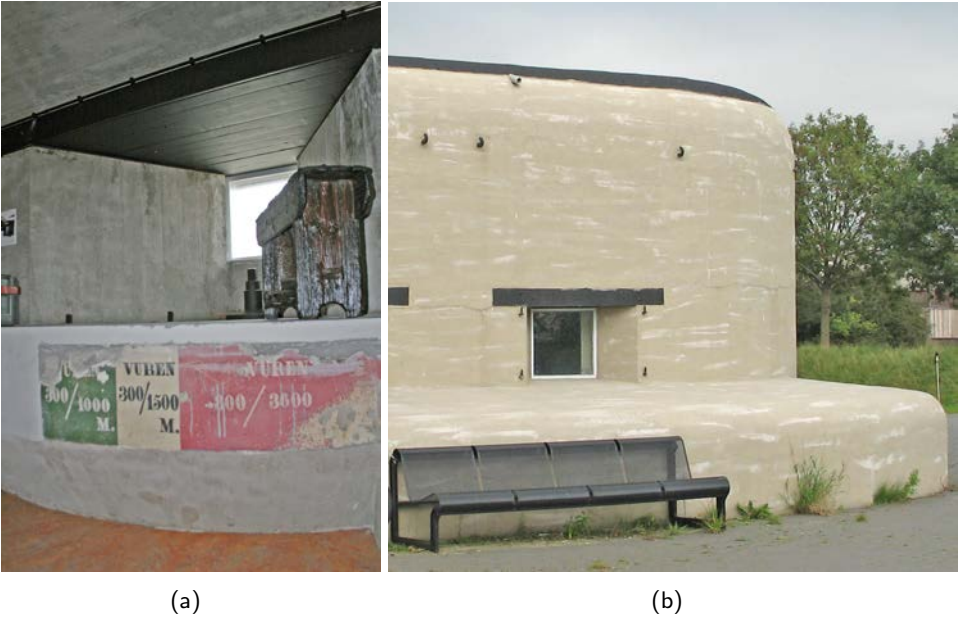


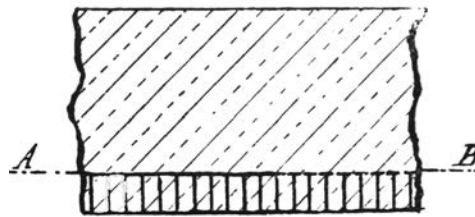
Figure 6.15 Use of standard profiles above the opening in a casemate of plain concrete (Fort near Vijfhuizen, 1899, situation 2006). a) Interior. b) Exterior.



(a)



(b)



(c)

Figure 6.16 Example of the use of railway profiles in plain concrete military construction to support slab constructions. a) Profiles placed below the slab (Fort near Hoofddorp, 1904, situation 2008). b) Profiles embedded in the concrete with visible flanges (Fort near Hoofddorp, 1904, situation 2008). c) Schematic drawing of embedding profiles in the concrete (Scharroo, 1909b).

Occasionally, rectangular profiles, called strips (Figures 6.17 and 6.18), were used as main reinforcement in the first decades of the 20th century (Probst, 1917, 1935). As secondary reinforcement, their use is often mentioned as a characteristic of the Hennebique system (Figure 6.19), especially in France (for example Boon, 1908, 1920; Scharroo, 1916; Van der Schrier, 1938; van Rossum, 1902). The use of only flat strips profiles was seldom (Figure 6.17), more common was the combination with plain reinforcing bars (Figures 6.18 and 6.20). A practical problem of using strips horizontally was to achieve a good embedding in the concrete as there was the tendency of the formation of voids under the strips (Memmler et al., 1907).

Standard profiles were commonly used for rigid reinforcement systems. In a rigid reinforcement system, the reinforcement is self-supporting and can even carry the weight of the formwork and of the fresh concrete during construction. As rigid systems did not require a secondary construction for the formwork, it made them attractive for spans over valleys. A practical requirement to be able to carry these additional loads was an exact execution of the reinforcement. The reinforcement was often designed as a lattice, using either flat strips or profiles. Known rigid reinforcement systems for bridges were the systems Wünsch, Melan, Ribera, von Emperger and Möller (Memmler et al., 1907). An example for a bridge influenced by the Melan system is the bridge over the Oostelijke Singelgracht in Utrecht, designed by Prof. A. W. C. Dwars and built in 1906 (Figure 6.21). The reinforcement is a lattice made from L- and U-sections (Sanders, 1907).

A different example of the use of a rigid reinforcement is the Hofplein railway viaduct in Rotterdam (1900-1908, Figure 6.22). In this case, the choice of a rigid reinforcement system was primarily based on the demand to achieve a durable concrete structure. Van Hemert feared movement of normal reinforcement during construction and tampering, which would not only reduce the thickness of the cover concrete but also influence the mechanical properties of the system. Therefore rigid reinforcement was chosen as the individual reinforcement members could not move; however, it was only applied for the first constructed part (built 1904, between the streets Simonstraat and Bergweg). The partially prefabricated reinforcement was a combination of L-sections, single T-sections, flat strips while on-site plain reinforcing bars were placed as secondary reinforcement. A drawback was that this system could not follow the curvature of the viaduct, therefore for the next part normal round reinforcement bars had to be used which were placed in a conventional way (Braak, 1907; Van Hemert, 1901, 1908).

An unusual use of profiles was found in the *Alpha-staal* (Figure 6.23), where a spiral formed round bar was welded to a double T-section. This reinforcement type was mainly applied for bridges, where the double T-section would perform as a beam under the concrete slab and the bar would be cast into the concrete slab (Van der Schrier, 1953).



Figure 6.17 Example of an unusual use of only rectangular reinforcement (bomb shelter near Fort Benoorden Spaarndam, 1916 - 1919, situation 2006, picture by T. G. Nijland).



Figure 6.18 Floor construction made with a combination of flat strips and round bars for reinforcement (Housing, The Hague, 1930s, exact year and architect unknown, situation 2009).



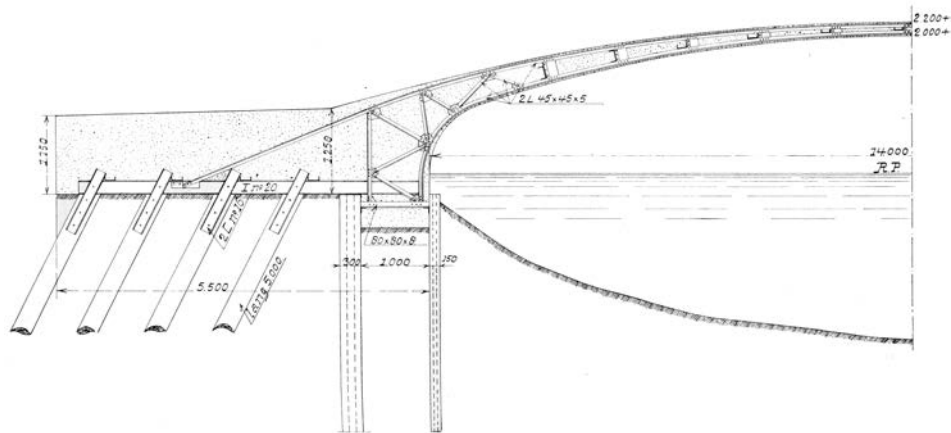
Figure 6.19 Example of the typical stirrups of the Hennebique system made with strips (former cotton warehouse Katoenveem Rotterdam, J. J. Kanter, 1920, situation 2009).



Figure 6.20 Stirrups made from strips in combination with plain reinforcing bars; notice the coupling of the bars above the strips and the annealed wires to connect the elements (emplacement of the Hofplein railway viaduct, Rotterdam, Van Hemert, 1904, situation 2009).

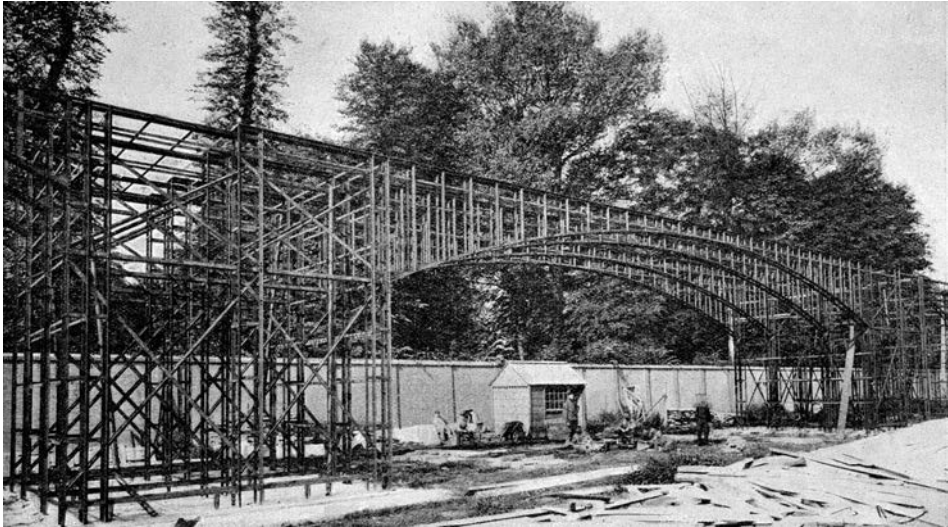


(a)

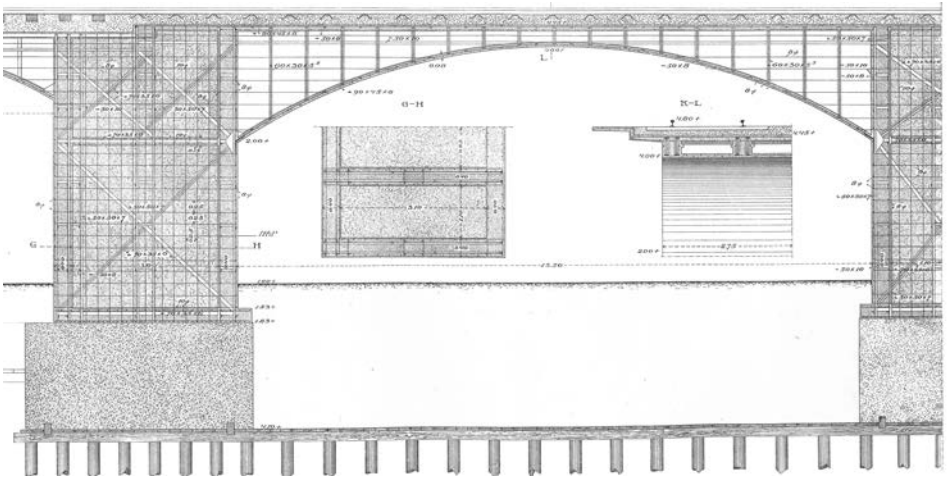


(b)

Figure 6.21 Oostelijke Singel bridge in Utrecht, now called Herenbrug made with rigid reinforcement using profiles (A. W. C. Dwars, 1906, situation 2011). a) The use of reinforced concrete is mainly noticeable due to the shape of the bridge, the bridge is clad with natural stone. b) Construction drawing of the reinforcement; notice that the bolts (or rivets) to connect the profiles are drawn as well (Sanders, 1907, p. 610).



(a)



(b)

Figure 6.22 Example of rigid reinforcement made from L, T and I sections (Hofplein railway viaduct, Rotterdam, Van Hemert, 1900-1908). a) Picture taken during construction showing the erected self-bearing reinforcement before the placing of the formwork (Bergsma & Homan van der Heide, 1910a, p. 303). b) Construction drawing of a span and abutments (Braak, 1907).

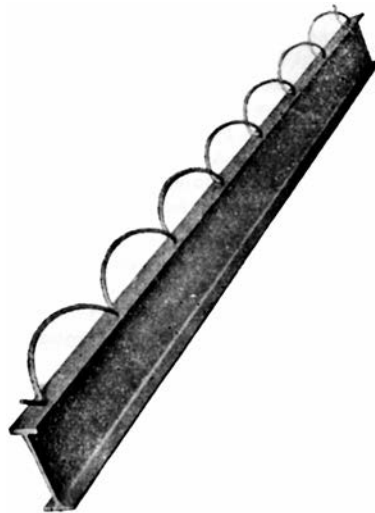


Figure 6.23 Alpha steel reinforcement (Van der Schrier, 1953, p. 47).

6.3.3 Patented reinforcement bars

Patented reinforcement bars were reinforcement bars specifically developed for reinforced concrete, contrary to standard profiles. The patent usually referred to the design of the reinforcement itself, or of the reinforced concrete. For the latter, this included design details and methods of calculation.

Patented reinforcement bars had a special texture or cross-section to improve the mechanical bond between the reinforcement and the concrete, and to distinguish themselves from other patented bars. In early Dutch concrete textbooks, special reinforcement bars were mentioned such as the Ransome, Thacher, Johnson and Kahn iron (Figure 6.24). Reference was made to their use in the United States of America, the United Kingdom or Germany, but not to their use in the Netherlands. Illustrating pictures from Dutch construction works used in these textbooks only show the use of plain reinforcing bars or standard profiles (Bergsma & Homan van der Heide, 1910a; Boon, 1908, 1913, 1920, 1931; Scharroo, 1916; van Rossum, 1902). Reference to these reinforcement systems is understandable; early Dutch concrete textbooks were strongly influenced by foreign traditions and publications, such as by Christophe (1902), Ast (1907), Büsing & Schumann (1905) and the series *Handbuch für den Eisenbetonbau* edited by *Von Emperger* (for example Foerster et al., 1908; Memmler et al., 1907; Spitzer et al., 1908). It is questionable to which extent these patented reinforcement bars were applied in the Netherlands as no reference was made to their use or their distribution and no examples are known. This can indicate a small-scale or even no application at all of some bars in the Netherlands.

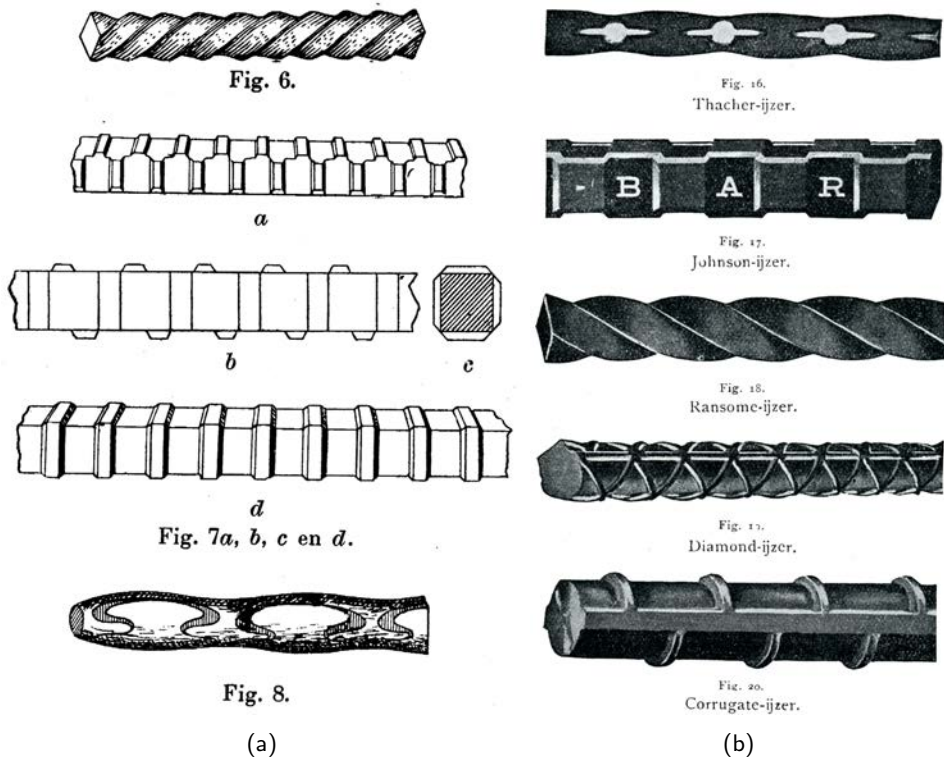
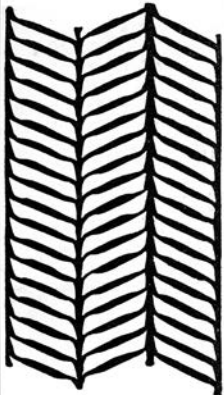


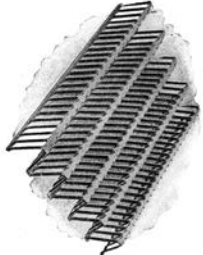
Figure 6.24 Examples of different reinforcement bars mentioned in Dutch literature. a) From top to bottom: Ransome iron, 3 different perspective of a Johnson iron and Thacher iron (Boon, 1908 p. 18). b) From top to bottom: Thacher iron, Johnson iron, Ransome iron, Diamond iron and Corrugate iron (Bergsma & Homan van der Heide, 1910a, p. 47).

An exception is the use of expanded metal (*metalgaas*), which was used for (internal) walls and secondary elements (Scharroo, 1910a). Dutch advertisements confirm the national distribution of this type of reinforcement (see Figure 6.25). Expanded metal was used in the Dutch reinforcement system for sea defences, the *De Muralt* system (Figure 6.26). An example for a dyke built with the *De Muralt* system can be found between the Dutch towns of Scharendijke and Den Osse in the province of Zeeland (Colby, 1909; Foerster et al., 1912; Scharroo, 1916; Van der Kloes, 1908c; Van der Kloes et al., 1924).

Haringgraatstaal.



Trussitgaas.



MOENS & BECK
□ Technisch Bureau □
BLOEMENDAAL.

HARINGGRAATSTAAL.
voor Cementijzer-Constructie.

TRUSSITGAAS.
voor betondaken.

DIAMANTGAAS.
voor kolommen in Cement-
ijzer-Constructie.

METAALGAAS.
(Métal Deployé).

HYDREX VILT.
voor het waterdicht bekleden
van werken in gewapend
Beton, zooals reservoirs,
viaducten, enz.

RUSTHAKEN.
ter vervanging van steiger-
werk.

Figure 6.25 Dutch advertisement for different types of expanded metal (Bergsma & Homan van der Heide, 1910a).

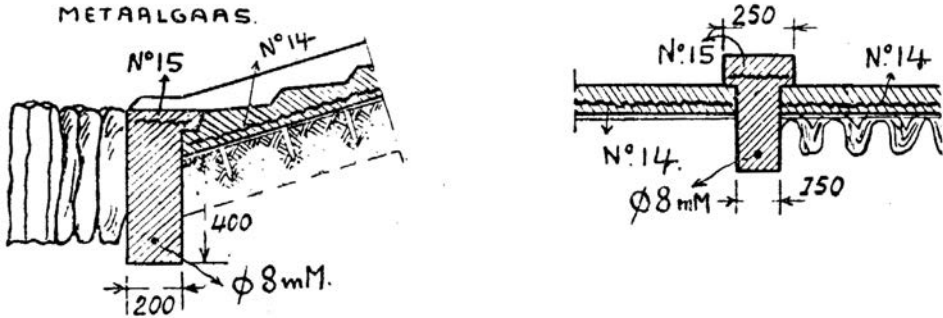


Fig. 334.

Figure 6.26 Schematic drawings of the sea defence system De Muralt; the numerical symbols No.14 and No.15 refer to type of expanded metal mesh (Bergsma & Homan van der Heide, 1910a, p. 256).

6.3.4 Cold worked twisted bars

Whereas modifying the cross-section and texture of bars improved the mechanical bond between the reinforcement and the concrete, twisting of the bars aimed at increasing their tensile strength. The Austrian Emil Probst (1877-1950) already discovered in 1917 that the tensile strength of the reinforcement bar could be increased by twisting, a cold working method. New reinforcement types based on this principle were the ISTEg-reinforcement bar,³ and the *Torstahl* (see Figures 6.27 to 6.29), which were introduced in the late 1920s and 1930s (Gantvoort, 1964).

The ISTEg-reinforcement bar (Figure 6.27), a twin twisted reinforcement bar, was produced by twisting two steel bars of St.37 quality together which increased the yield strength up to 50% and the tensile strength up to 10%. Although production costs were higher than for normal steel, their application could be economically beneficial as a lower steel quantity could be used. It was advised as tensile reinforcement, as under compressive loads the higher tensile strength of the bars were not fully utilised (Anon., 1927b; Probst, 1935; Scharroo, 1942a; Van der Schrier, 1938).

An exception is the *drillwulststaal* or *getordeerd kruisstaal*, which appeared in the late 1930s (Figure 6.28). The twisting of the bars did not aim at increasing the strength but at increasing the bond between the concrete and reinforcement. The used steel quality was initially a normal QR22 with a cross section, later high quality steel was used (Van der Schrier, 1938).

Some twisted ribbed reinforcement bars were produced in the Netherlands by importing ribbed reinforcement bars and cold working them locally. One example is the *Torwastaal* (see Figure 6.29), which was produced after the Second World War by the *N.V. Rotterdamsche Beton- en Aann. Mij v.h. van Wanینگ & Co*, and distributed by *N.V. Montan IJzer en Staal*. Normal ribbed bars of QR22 quality were partially flattened to an oval shape and thereafter twisted. This treatment increased the tensile strength and the bond between the concrete and reinforcement, which made it comparable to a steel of QRn48 quality (Sw., 1950; Van der Schrier, 1951, 1968). The use of *Torwastaal*, compared to normal reinforcing steel, could reduce costs by 4–8%. Initially, warnings were given of quality fluctuations due to the use of different suppliers (Sw., 1950).

Torstahl (Figure 6.30) is characterised by two longitudinal ribs with transverse ribs in between. It was made from a QR24 and after twisting, it had QRn40 quality (Scharroo, 1944; Van der Schrier, 1942, 1968). It was one of the commonly applied ribbed reinforcement bars in the Netherlands and produced in Germany and Belgium (Gantvoort, 1964). Steel quantity could be reduced up to 30% when high quality steel such as *Torstahl* was used (Welling, 1953).

³ISTEG is an acronym for the Austrian *Internationale Stegdeckenbetongesellschaft*.

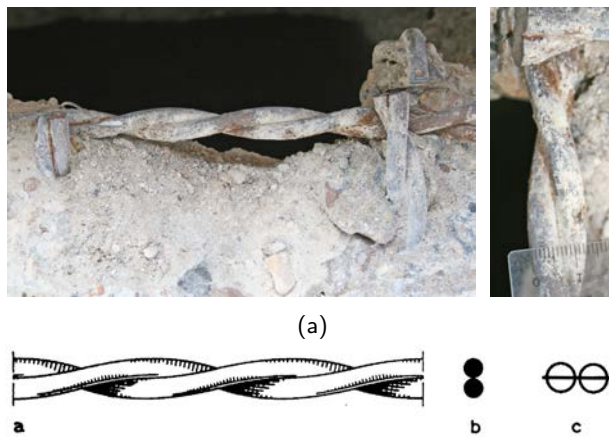


Fig. 30. Aanzicht (a), doorsnede (b) en symbool (c) van Istege-staal.

(b)

Figure 6.27 ISTEGB bar. a) Example of application (former Gele Scheikunde, TU Delft, G. C. Bremer & H. L. Engberts, 1936-1938, situation 2010). b) Drawings of the view, section and symbol (Van der Schrier, 1953, p. 44).

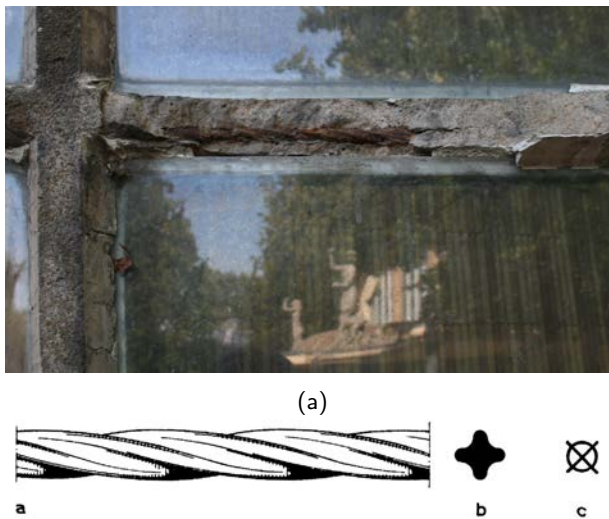


Fig. 31. Aanzicht (a), doorsnede (b) en symbool (c) van getordeerd-kruisstaal.

(b)

Figure 6.28 Getordeerd kruisstaal (*Drillwulststaal*). a) Prefabricated concrete window frames with exposed twisted reinforcement due to spalling, probably *getordeerd-kruisstaal* (*Rivierahal, Zoo Blijdorp*, Rotterdam, S. van Ravesteyn, 1939-1941, situation 2010). b) Drawings of the view, section and symbol (Van der Schrier, 1953, p. 44).



Figure 6.29 Drawing of view and section of a *Torwastal* (Gantvoort, 1964).

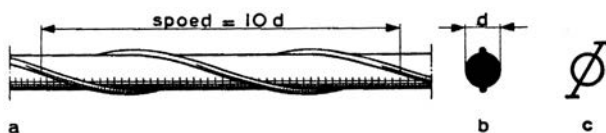


fig. 33. Aanzicht (a), doorsnede (b) en symbool (c) van torstaal.

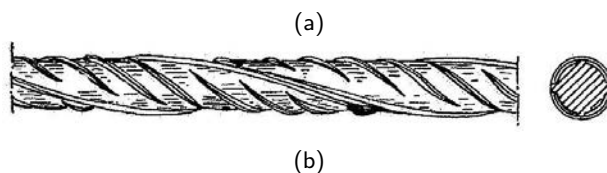


Figure 6.30 Drawing of the view, section and symbol of a *Torstaal*. a) Without ribs (Van der Schrier, 1953, p. 46). b) With ribs (Gantvoort, 1964).



Figure 6.31 Ribbed reinforcement bars visible after demolition of a building on the Calve factory grounds probably dating back from the early 1960s (see Stenvert & Dekker, 2009)

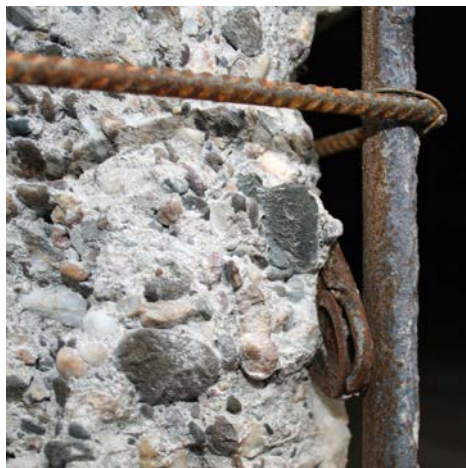


Figure 6.32 Textural differences between historic and modern reinforcement (circumambulation passageway, Pilgrimage church, Brielle, 1912, situation 2010).

6.3.5 Ribbed reinforcement bars

Ribbed reinforcing steel is defined as having “*at least two rows of transverse ribs, which are uniformly distributed over the entire length*” (NEN-EN 10080:2005). This is the most common reinforcement type now used for reinforced concrete (Figures 6.31 and 6.32). They combine the advantages of easy placing and calculation of plain reinforcement bars with the increased mechanical bond between the previously used special patented reinforcement bars. Using ribbed bars had also the advantage of spreading possible cracks more evenly (Dicke, 1966). Two groups of ribbed reinforcement bars existed: bars with ribs and bars with ribs which were twisted (see Section 6.3.4).

Whereas ribbed twisted bars were discussed in Dutch textbooks prior to the Second World War, normal ribbed reinforcement bars were only mentioned from the 1950s onwards. Rib reinforcement bars were initially made with high quality, warm rolled reinforcement steel, which had a higher quality due to its material composition and not due to cold treatment. Therefore they were more expensive and less popular.

Reinforcement bars of a normal quality QR24 and with a ribbed profile only started to appear in 1964 (Van der Schrier, 1968). The advantages were that the ribbed bars reduced the labour costs as it was not necessary to bend the ends to avoid slipping (Figure 6.14). A practical obstacle was the confusion with the similar ribbed QR40. A temporary solution until the textures would be standardised by a EURONORM was to make the ribs of QR40 transverse, the ribs of QR24 perpendicular to the axis, or at least V-shaped. The Dutch steel producer *Hoogovens* adapted its production to these requirements (Dicke, 1966). Most ribbed bars were, however, imported from Germany, Belgium, Luxembourg or France (Gantvoort, 1964). One example for a Dutch produced ribbed reinforcement bar was the *Kamstaal* or *Demka kamstaal*, produced by *Koninklijke Demka Staalfabrieken N.V.* in Utrecht (Figure 6.33b). It had a quality of QR40 and transverse ribs which were perpendicular to the axis (Gantvoort, 1964; Van der Schrier, 1951, 1960, 1968). An overview of different ribbed reinforcement types used in the Netherlands in the 1960s is given in Figure 6.33.

6.3.6 Welded wire meshes

Welded wire meshes, or welded fabric, are defined as an “*arrangement of longitudinal and transverse bars, rods or wires of the same or different nominal diameter and length that are arranged substantially at right angles to each other and factory electrical resistance welded together by automatic machines at all points of intersection*” (NEN-EN 10080:2005). This current definition still suits the welded wire meshes used in historic concrete (Figure 6.34). Welded wire meshes are prefabricated meshes made from cold worked steel bars (Siemens-Martin steel) with a diameter of 3.4 to 12 mm. The individual bars are electrically welded. Meshes made from bars with a maximum diameter of 6 mm were delivered on-site as rolls

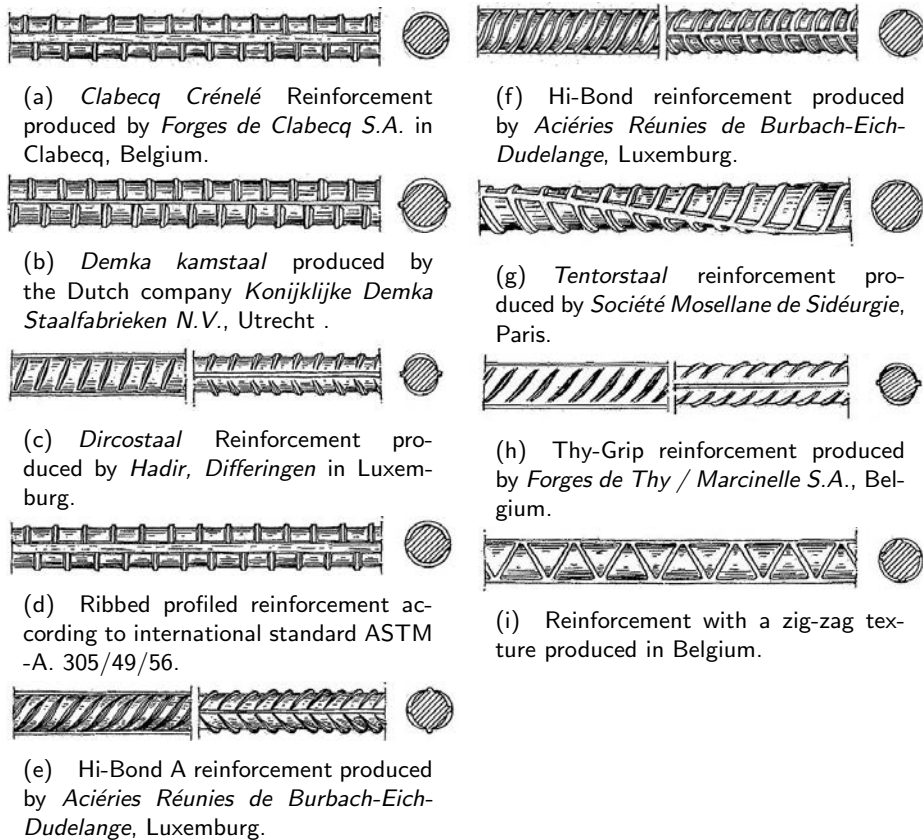


Figure 6.33 Drawings of the view and section of the most commonly used ribbed reinforcement bars used in the 1960s in the Netherlands (Gantvoort, 1964).

or as mats. They were first used in Germany and in the United States of America in the 1920s (Gantvoort, 1964); in the Netherlands, their use emerged in the late 1920s. Due to their numerous advantages, the use of welded meshes increased in the 1930s (Scharroo, 1946) and in a second wave in the 1960s (Gantvoort, 1964). Welded wire meshes were for the first time addressed and categorised as profiled reinforcement in the G.B.V. 1962, art. 17.

The advantages of using welded wire meshes instead of individual reinforcement bars were the higher tensile strength. The bars had a higher slip resistance giving the concrete a higher resistance towards cracking, and a better reliability of placing the bars at the right location, and allowed a lower reinforcement percentage. The construction was simplified and quicker as the individual bars did not need to be connected (Anon., 1932b; Gantvoort, 1964; Probst, 1935; Scharroo, 1946).

The terminology for welded wire meshes was initially influenced by the German terminology. The German term *Baustahlgewebe*, the brand name of the German

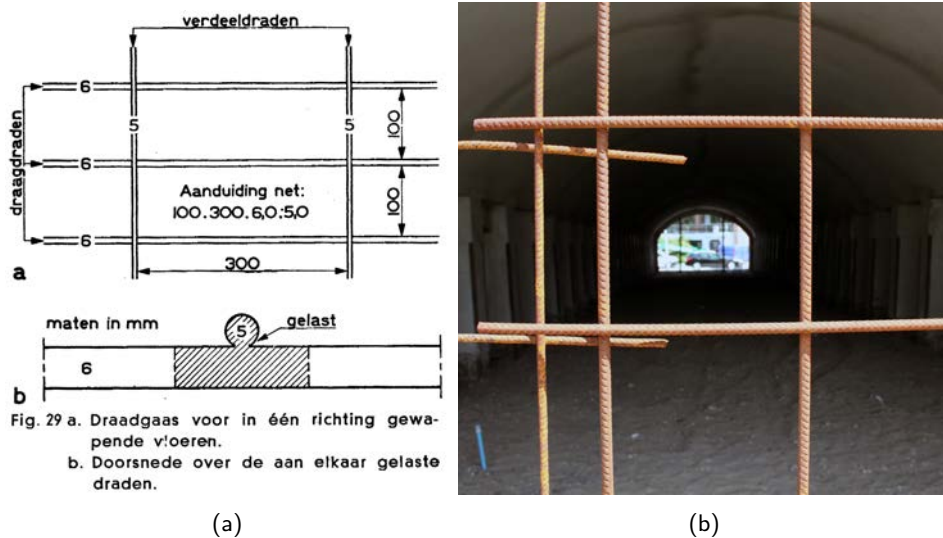


Figure 6.34 Comparison of a historic and present day welded mesh. a) Drawing of the section of welded wire meshes, with a distance of 10 cm between the main reinforcement and 30 cm for the secondary reinforcement, between the bars (Van der Schrier, 1953, p. 43). b) For comparison, picture of a present day mesh made with ribbed bars (emplacement of the Hofplein railway viaduct, Rotterdam, Van Hemert 1904, situation 2009).

company *Bau-Stahlgewebe G.m.b.H.*, was used for a long time, parallel to the Dutch *draadgaas*; a more recent term was *betonstaalmatten* (Gantvoort, 1964). The changing terminology was independent of the thickness of the meshes. The welded wire meshes used in the Netherlands were initially imported from Germany (Van der Schrier, 1938, 1942, 1949, 1951).

Prior to the introduction of welded wire meshes, wire meshes using thinner diameters were occasionally used. An unusual use of thinner wire meshes (*draadgaas*) was invented by Van der Kloes in the late 1920s, who proposed it as formwork for plain light concrete structures; the wire mesh would remain in the hardened concrete and serve as lathwork for plaster. The technique was applied for external walls of housing projects, however a successful widespread application was doubted due to the risk of corrosion of the meshes and as the mesh did not have any structural use (Scharroo, 1932).

6.4 Connection of the reinforcement

The original intention to tie the individual bars together, a time consuming process, was to secure the location of the bars according to the calculations (Figures 6.35 and 6.36). Considering the durability and the possibility of conservation, the way

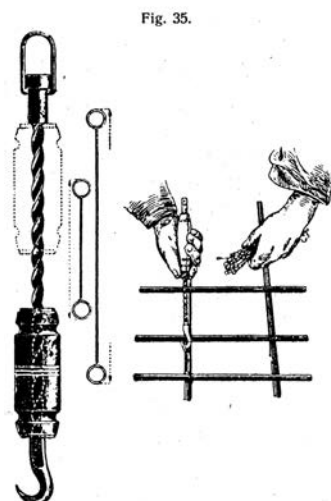


Figure 6.35 Connection of main and secondary reinforcement with annealed wires, left showing tool used to twist the wires (Scharroo, 1916, page 111).

KELDER ONDER HET GEBOUW VAN „DE ALGEMEENE“, DAMRAK AMSTERDAM. — HET NETWERK WORDT GEVLOCHTEN.

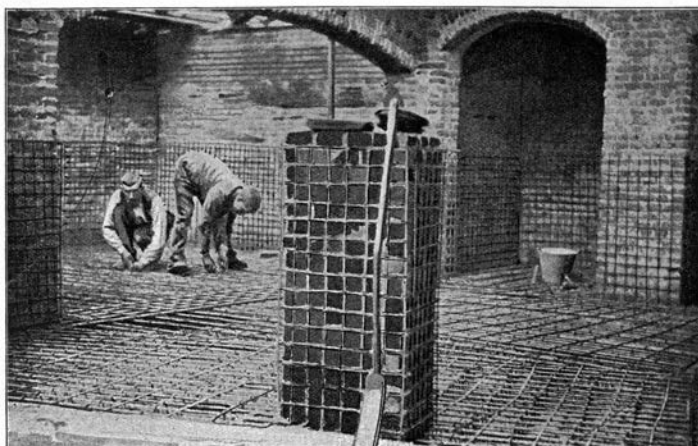


Fig. 254.

Figure 6.36 Picture showing the manual connecting of bars with wires (Bergsma & Homan van der Heide, 1910a, p. 164).

the individual reinforcement members were connected is of interest. The quality of the connection influenced the position of the reinforcement and the homogeneity of the concrete. The homogeneity could be affected during construction, if for example, bars moved and came too close; thereby it would have been harder for larger aggregates to pass between the bars. In case of movement of the reinforcement bars, the thickness of the concrete cover (see Section 6.5) could be reduced. When applying electrochemical repair techniques, the continuity of electrical conductivity of the reinforcement is relevant (see Section 9.4.5).

Usually, the main reinforcement bars were connected to a perpendicular placed secondary reinforcement. As bars were not always available in the required length, it was sometimes necessary to extend bars in a way which allowed load transfer. All these connections had to be sufficiently rigid to prevent a movement of the bars during construction due to (undesired) walking on the reinforcement, and pouring and compaction of the concrete. The skills required to place and connect the reinforcement led to the development of an own profession, the *betonvlechter* (literally “concrete weaver”, steel bender). In present day concrete construction, the dislocation of the reinforcement is partially prevented by using welded wire meshes or welding individual bars, occasionally by tying the bars. However, welding technology only significantly progressed during and after the First World War. Suitable welding electrodes for electric arc welding only became available in the 1920s. Its usability for construction works was explored in the 1930s (for example Van Genderen Stort, 1931).

Therefore, other methods were applied such as using wires, rivets, bolts, or weaving. Sometimes the bars were not connected, as for example the bars in a Hennebique system (Christophe, 1905; Marsh, 1904; Memmler et al., 1907). The most common technique was to use annealed wires to connect the transverse and longitudinal bars (Figures 6.37 and 6.38). This can be often encountered in the Monier system and the later more common, non-proprietary reinforced concrete systems using plain circular bars (Betonvereeniging, 1929; Boon, 1908; Marsh, 1904; Memmler et al., 1907; Scharroo, 1910a, 1916). A seldom applied technique in the Netherlands was to weave thin bars as it was done for example in the Cottançin system. A Dutch example for a woven reinforcement can be seen in Figure 6.39.

For rigid reinforcement systems the quality of the connection itself was even statically relevant. These systems showed a strong resemblance to iron framework construction, and unsurprisingly used the same connection methods: rivets and bolts (see Figures 6.21 and 6.22). As the bolts and rivets required holes in the profile, it weakened the cross-section of the profile (Van Genderen Stort, 1931). In the previously mentioned Hofplein railway viaduct (see Section 6.3.2), the individual profiles were connected with bolts. Van Hemert (1901) was well aware that a rigid system would increase the total required amount of iron in the cross-section in order to compensate the loss due to the bolt holes. Nevertheless, it was necessary to assemble the individual prefabricated reinforcement elements.

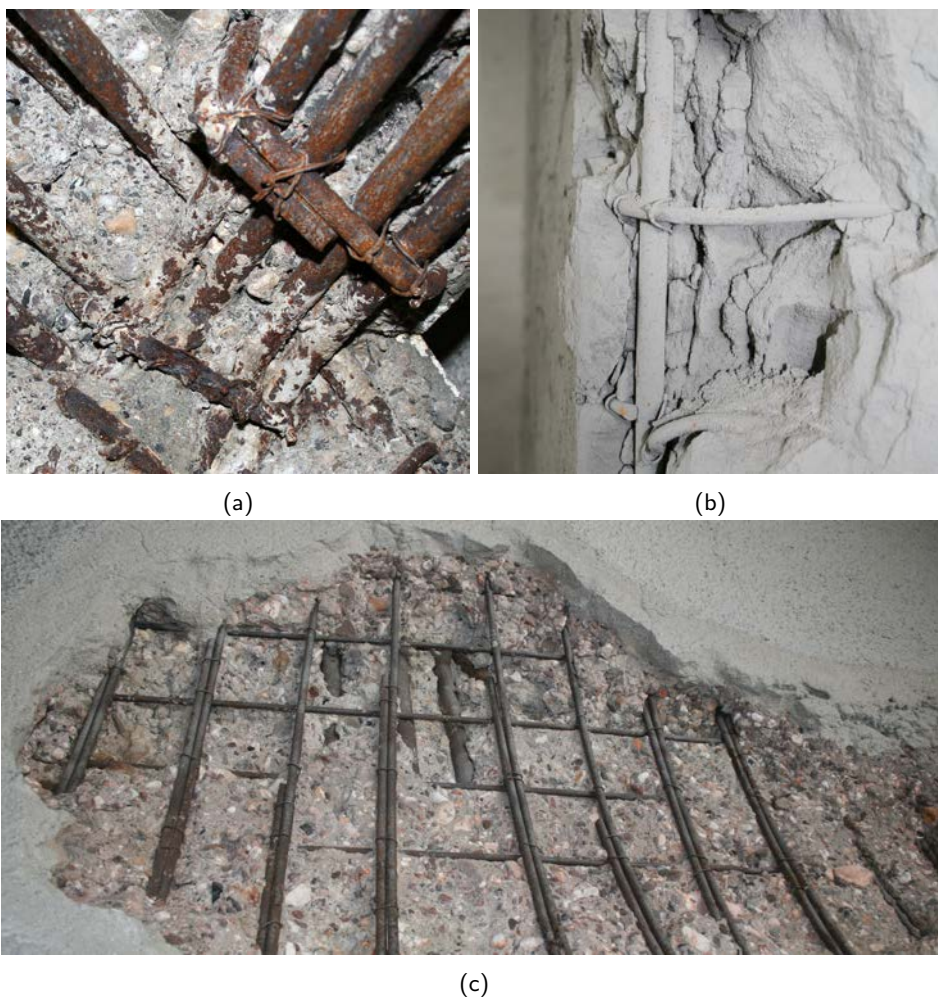


Figure 6.37 Examples of connections made with annealed wires. a) Connection of plain reinforcement bars with stirrups at the crossing point of two beams (circumambulation passageway, Pilgrimage church, Brielle, 1912, situation 2010 after hydrodemolition). b) Wire connection of stirrups with reinforcement bar; during the intervention the column was painted grey and the reinforcement left exposed (Lichttoren, Philips building ED, Eindhoven; Bureau TABROS 1920/21, situation 2007 after intervention). c) Extension of reinforcement bars in a vault with wires, notice the thicker bars in the back (emplacement of the Hofplein railway viaduct, Rotterdam, 1904, situation 2009 after hydrodemolition and partial application of sprayed concrete).

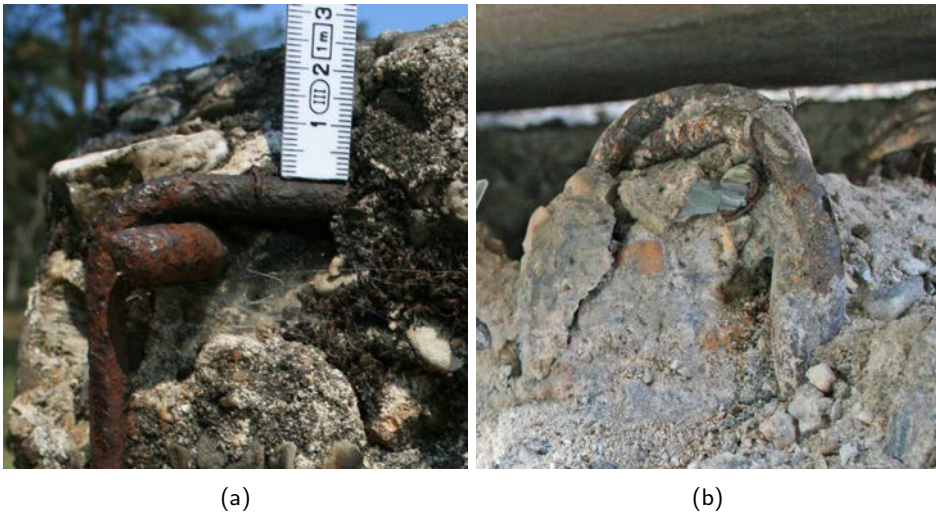


Figure 6.38 Examples of wired connections. a) Partially corroded wire to connect horizontal reinforcement bar with a stirrup (left of ruler) (Unfinished *Groot Museum*, National Park *Hoge Veluwe*, H. van der Velde, 1921-1922, situation 2008). b) ISTE bars connected with wires (Gele Scheikunde, TU Delft, G. C. Bremer & H. L. Engberts, 1936-1938, situation 2010 during partial demolition).

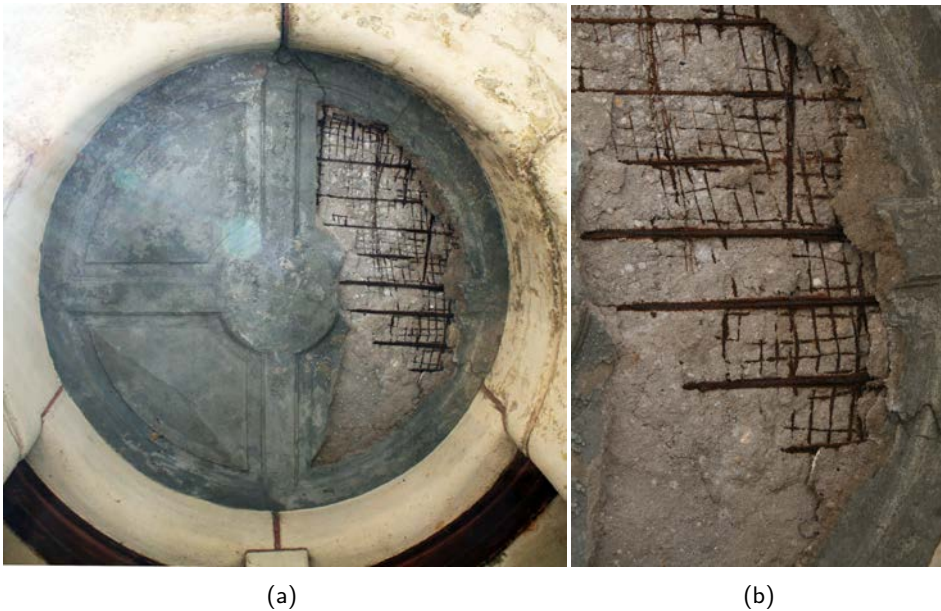


Figure 6.39 Reinforcement of a balcony soffit with plain round bars as main reinforcement and a woven secondary reinforcement (former office building of the *Rotterdamsche Cementsteenfabriek van Waning & Co*, Rotterdam, J. I. van Waning, 1898, situation 2010). Notice the small amount of coarse aggregates present. a) Full image. b) Detail.



Fig. 142.



Fig. 143.



Figure 6.40 Connection to extend bars with wires (left) and with coupling (right), (Boon, 1908, p. 78).

Figure 6.41 Example of a coupling of vertical reinforcement bars above a horizontal stirrups made with strips (emplacement of the Hofplein railway viaduct, Rotterdam, 1904, situation 2009).

Only in the 1930s, wide scale application of welding to connect longitudinal and transverse reinforcement bars appeared with the introduction of welded wire meshes (see Section 6.3.6). The welding for the extension of bars is mentioned already earlier (Christophe, 1905; Memmler et al., 1907). A practical limitation of welding the reinforcement on-site were that *vloeiijzer* (weld iron) was more difficult to weld and that the tensile strength at the welding point was reduced. Therefore it was advised to avoid welding (Memmler et al., 1907).

As reinforcement bars could not always be delivered in the required length, it was necessary to connect the bars, either by coupling, using annealed wires or welding (Figures 6.40 and 6.41). The choice of connection type depended on whether tensile or compressive loads had to be transferred. The connection with wires was advised for secondary reinforcement bars and for bars with a relatively small diameter (Christophe, 1905). An overlap of the bars of 10-20 cm (Boon, 1908), or, depending on the bar diameter, for example a length of 20 – 30 times the diameter, was advised (Memmler et al., 1907; Scharroo, 1929). This technique was also applied to vertical bars in columns of multi-storey buildings (Boon, 1908). Other authors advised not to connect the bars with wires, even considering it wrong; instead, the bars should overlap and be placed with sufficient distance, for example 2 cm, to embed both bars well in the concrete to ensure sufficient adhesion to transfer the stresses (Bergsma, 1934; Betonvereniging, 1929; Memmler et al., 1907; Van der Schrier, 1960). For bars with a large diameter and for bars exposed to compressive loads, the use of couplings was advised. In case tensile length had to be transferred, the coupling was threaded (Boon, 1908; Christophe, 1905).

6.5 Concrete cover of the reinforcement

Reviewing the development of the role of the concrete cover, it can be observed that the importance attributed to the concrete cover and its quality slowly developed over time, reflecting the insight into concrete durability. From a statical point of view, the preferred location of the reinforcement is in the tensile zone. For slabs and beams, this would mean as close to the bottom as possible. Yet, already early on, it was understood that such a position would lead to too much exposure of the reinforcement to potential harmful conditions, for example fire. Fire was seen then as the main threat to reinforcement, based on the poor performance of iron structures when exposed to fire. The better performance during fire was one of the reasons why reinforced concrete became appreciated for public buildings and one of its selling points. In this context, a minimum thickness of the cover concrete was required and discussed in textbooks early on. For fire protection, a minimum thickness of the concrete cover of 1-2 cm resp. 1.5 inch was advised (Sang, 1910; Scharroo, 1910a; Taylor & Thompson, 1905).

A later motive to embed the reinforcement in the concrete was to prevent corrosion of the reinforcement, although it was initially not entirely understood why and how the reinforcement was protected in the concrete. Nowadays, it is known that the alkaline environment of the concrete protects the reinforcement from corrosion and a protecting passivity layer is formed around the reinforcement. However, carbonation, which is a normal process in concrete, reduces the alkalinity of the concrete and under certain circumstances can induce corrosion. Therefore, the thickness, quality and density of the concrete cover are relevant, as the carbonation initiates at the surface of the concrete which is exposed to CO_2 . The carbonation rate is not linear and slows down with time, and depends on the moisture content in the concrete (indoors, outside but sheltered, horizontal etc.). Another influencing factor is the porosity of the concrete and the presence of voids and cracks, through which CO_2 can ingress, leading to a deeper carbonation front. Corrosion can also be induced by chlorides, which were either introduced into the concrete during construction (Section 5.4), or from external sources such as seawater or de-icing agents. To prevent that these harmful agents reach the reinforcement and initiate corrosion, the quality and the thickness of the cover is relevant.

The initial assumption was that reinforced concrete is a very durable material if executed well. Therefore, it was not considered necessary to design the structure according to durability demands as it is done today. Concerning the risk of corrosion, the assumption was that if the cover was of a sufficient density and quality, the reinforcement would be protected. An early concern was the risk of corrosion due to stray currents, and had been discussed early on, often in combination with bridges for electrical railways (for example Bergsma, 1934). The density and quality of the cover concrete are still considered to be important factors to prevent corrosion, yet the thickness of the concrete cover is now considered as well.

The question why the reinforcement did not corrode in the concrete was an early research topic, as the usability of reinforced concrete depended on it. Several theories on the principles of protection of the reinforcement against corrosion were discussed at the beginning of the 20th century, ranging from the Rohland's theory of the formation of a protective alkaline environment in the concrete (Probst, 1917), which is still considered as correct, to Breuillé's theory of the reaction between the cement and the iron leading to the formation of a proactive layer of ferrous silicates around the iron bar (Christophe, 1905; Probst, 1917; Verhey, 1912). The good condition of the reinforcement of demolished reinforced concrete structures and of lab tests was seen as empiric evidence that the reinforcement was protected from corrosion in the concrete (Christophe, 1905; Memmler et al., 1907; Scharroo, 1916; Verhey, 1912). It was assumed that if the reinforcement was well embedded in the concrete, it would be protected from corrosion. The advice was a good execution of the works, to avoid air pockets near the reinforcement and to use a wet and rich concrete mix (Boon, 1908; Sang, 1910). A wet mix was considered necessary, as the concrete was still manually compacted and a wetter mix could flow better around the reinforcement; however it is known now that with higher water content the density of the concrete cover is reduced.

In the Interwar period, cases of reinforcement corrosion drew attention to possible insufficient thickness of the concrete cover in relation with cracking of the concrete surface and the possibility of ingress of harmful agents through these cracks (Scharroo, 1921). Extreme environments, such as exposure to sea water, humidity and flue gasses were then considered, requiring an increase of the thickness of the concrete cover (Groothoff, 1950; Probst, 1935; Van der Schrier, 1938, 1942). In the 1950s, other causes for corrosion besides stray currents became finally accepted (Broomfield, 2007). An example is corrosion due to carbonation, where the influence of the thickness of the cover concrete on the risk of corrosion was understood; yet it was admitted that concrete technology was still too young to answer the question of which cover thickness would be sufficient. A preventive design with an increased thickness was not feasible as a too thick cover was considered to cause shrinkage of the fresh concrete and would increase costs (Josephus Jitta, 1950). The newness of this concept is reflected in the fact that this damage mechanism is not discussed in the historic concrete textbooks reviewed.

The importance of the concrete cover is acknowledged in present day standards and is considered as one of the main factors influencing the durability of reinforced concrete. The *"corrosion protection of steel reinforcement depends on density, quality and thickness of concrete cover [...] and cracking [...]. The cover density and quality is achieved by controlling the maximum water/cement ratio and minimum cement content [...] and may be related to a minimum strength class of concrete."* (EN 1992-1-1:2004 Eurocode 2). As the protection of the reinforcement from fire was already a concern, a minimum thickness of the concrete cover was required in the first edition of the G.B.V. 1912. The required minimum thickness was 10 mm for slabs, and 15 mm for beams and columns. In general, the minimum thickness increased with time, yet more significantly a differentiation of exposure

classes was made (Table 6.3). The term *betondekking* (concrete cover) is for the first introduced in the G.B.V. 1918 in the heading of an article.

A rudimentary concept of exposure classes was for the first time introduced in the G.B.V. 1918 in the form of exposure to high temperatures. In such cases, an additional cover of 10 mm to the normal thickness was required. In the 1920s, the insight into concrete durability increased and was reflected in the 1930 edition of the G.B.V., where besides exposure to fire, also aggressive environments such as sea water, aggressive water and gases required an increased concrete cover. Due to practical experience, another category was introduced for works which could not be controlled after construction, such as foundations. In the 1950 edition, for the first time wet and dry cycles are considered as a separate exposure class in the form of exposure to “*wind en weer*” (wind and weather). The exposure to humidity in general was not considered, as it was for example later done in the *Voorschriften Beton Technologie* (VBT 1995, NEN-EN 5950:1995, *Regulations for concrete. Technology*, see Table 6.4). In present day standards, the exposure classes are a combination of the degradation mechanism (corrosion, freeze thaw attack and chemical attack) and the environmental conditions, including the exposure to different moisture degrees (see Table 6.5). In combination with the structural class of the concrete member, the exposure class defines the thickness of the concrete cover (EN 1992-1-1:2004 Eurocode 2).

Initially, no reference point was given for measuring of the thickness of the concrete cover, such as the main reinforcement or stirrups. In the G.B.V. 1918, the main reinforcement is named as reference point for the thickness. In the G.B.V. 1930, it is clearly stated that a layer of render cannot be seen as part of the concrete cover. The consideration of render as part of the concrete cover did occur. For example, in the Prussian draft of the code of practice for reinforced concrete (*Vorläufige Leitsätze für die Vorbereitung, Ausführung und Prüfung von Eisenbetonbauten*) from 1904, it was allowed to reduce the thickness of the concrete cover, if the bars had a smaller diameter than 1cm and a plaster was applied; in the 1907 code this option is not mentioned anymore (Fingerloos, 2009).

In the G.B.V. 1950, a significant change is made concerning the reference point for the measuring of the thickness of the cover: instead of the main reinforcement, the reinforcement nearest to the surface is used, which now can refer to secondary reinforcement elements such as stirrups or shrinkage reinforcement (see Figure 6.42). The values given in the G.B.V. 1950 can give the impression that thickness is reduced compared to the 1940 edition, but in fact the designed thickness can be similar or even higher as the values are corrected by the thickness of the secondary reinforcement. This reference point introduced in the G.B.V. 1950 is still used nowadays when defining the thickness of the concrete cover: “*the distance between the surface of the reinforcement closest to the nearest concrete surface (including links and stirrups and surface reinforcement where relevant) and the nearest concrete surface.[...] The nominal cover [...] is defined as a minimum cover, $c_{\min}$ [...], plus an allowance in design for deviation, c_{dev} .*” (EN 1992-1-1:2004 Eurocode 2).

Table 6.3 Minimum concrete cover (mm) required in the different editions of the G.B.V.

	Slabs			Beams			Columns			Additional cover			
	Exposure classes			Exposure classes			Exposure classes						
	No special exposure class	Exposed to wind and weather	No control of surface after casting possible	Aggressive environments ^a	No special exposure class	Exposed to the wind and weather	No control of surface after casting possible	Aggressive environments ^a	No special exposure class	Exposed to wind and weather	No control of surface after casting possible	Aggressive environments ^a	Surface treatment which damages the cement film
Reference point													
Concept Betonijzer-voorschriften 1909 art. 15	◇ 10				15				15				
G.B.V. 1912 art. 15	◇ 10 ^b				15				15				
G.B.V. 1918 art. 17	† 10 ^b			20 ^c	25			35 ^c	35			50 ^c	
G.B.V. 1930 art. 13	† 10		20	20	25		35	35	35			50	
G.B.V. 1940 art. 13	† 10		20	+10	25		35	+10	35			+10	+10
G.B.V. 1950 art. 13	○ d≤12 cm:10 ^d d>12 cm:15	15 ^d	20	+10	20	25	40	+10	30	35	40	+10	+10
G.B.V. 1962 art. 28	○ 10	15	20 ^e	+10	20	25 ^e	30	+10	25	30	35	+10	+10
Comparison													
	Slabs, walls			Beams, poer ^f , console									
	Exposure classes according to NEN-EN 5950:1995, see Table 6.4												
NEN 6720:1995 Voorschriften	1 2	3, 4, 5		1	2	3, 4, 5	1	2	3, 4, 5	1	2	3, 4, 5	
Beton TGB 1990	○ 15 25	30		25	30	35	30	35	40				+5

◇ None defined. † Main reinforcement. ○ Outer reinforcement.
a) High temperatures due to fire, sea water, aggressive water or gases. b) Valid for all other elements which are neither beams nor columns. c) Only for possible exposure to fire. d) Valid for walls and slabs. e) Includes now also contact to soil and ground water. f) Special type of foundation block.

Table 6.4 Exposure classes according to NEN 5950:1995 VBT 1995 (NEN-EN 5950:1995).

Exposure class	Environment
1	Dry
2	Wet
3	Wet in combination with de-icing agent
4	Seawater
5 (a,b,c,d)	Aggressive (slightly, moderate, highly or very highly)

Table 6.5 Exposure classes related to the environmental conditions according to EN 1992-1-1: 2004 Eurocode 2, table 4.1

Class designation	Description of the environment
1 No risk of corrosion	
X0	Concrete without reinforcement or embedded metal [...] very dry environment
2 Corrosion induced by carbonation	
XC1	Dry or permanently wet
XC2	Wet, rarely dry
XC3	Moderate humidity
XC4	Cyclic wet and dry
3 Corrosion induced by chlorides other than by seawater	
XD1	Moderate humidity
XD2	Wet, rarely dry
XD3	Cyclic wet and dry
4 Corrosion induced by chlorides by seawater	
XS1	Exposed to airborne salt but not in direct contact with the seawater
XS2	Permanently submerged
XS3	Tidal, splash and spray zones
5 Freeze-Thaw attack	
XF1	Moderate water saturation without de-icing agent
XF2	Moderate water saturation with de-icing agent
XF3	High water saturation without de-icing agent
XF4	High water saturation with de-icing agent or seawater
6 Chemical attack	
XA1	Slightly aggressive, chemical environment according to EN 206-1 Table 2
XA2	Moderate aggressive, chemical environment according to EN 206-1 Table 2
XA3	Highly aggressive, chemical environment according to EN 206-1 Table 2

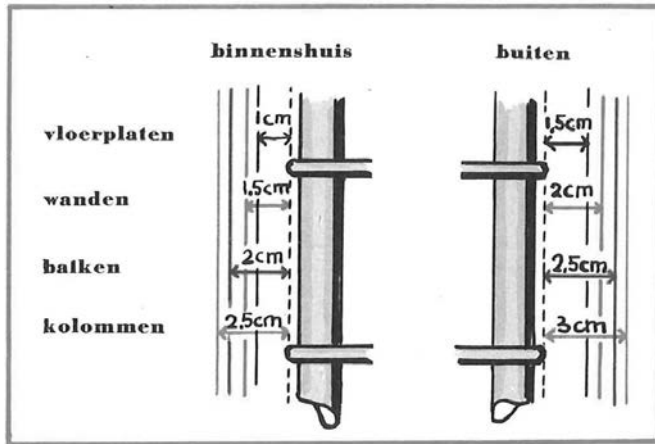


Figure 6.42 Drawing explaining the concrete cover according to the G.B.V. 1962; the thickness refers to the outer reinforcement. Left side for interior situations, right for exterior, from top to bottom: slabs, walls, beams and columns (Anon., 1968, p. 71).

The protective function and thickness of the concrete cover could be reduced by surface finishes. From the G.B.V. 1940 on, the increased application of tooled surface finishes is reflected on the demand to increase the thickness by 10 mm if the surface is to be treated in a way that will affect the cement film (e.g. bush hammering, sand or grit blasting, washing out with diluted acid). In practice, the thickness of the concrete cover could deviate due to a displacement of the reinforcement during construction (Figure 6.43), sometimes even leading to the exposure of the reinforcement after the striking of the formwork (for example Boon, 1931; Grin & van der Veen, 1950). This could not only affect the structural performance of the reinforced concrete, but also the durability of the structure.

Different methods were therefore applied to secure the position of the reinforcement during construction. One early option for horizontal elements such as slabs and beams was to pour first the concrete layer below the reinforcement, place the reinforcement and then continue with the pouring of the remaining concrete above the reinforcement (Christophe, 1905). Another option was to place small wooden blocks with the required height below the reinforcement, which would be removed after the striking of the formwork and the holes filled with mortar (Scharroo, 1910a, 1921, 1946). A more sophisticated option was available in the Netherlands from 1912 onwards, where small concrete blocks were placed under the reinforcement of horizontal concrete elements; these blocks could be attached to the reinforcement with wires (Figure 6.44). The blocks were available in the required cover thickness according to the G.B.V. (Boon, 1931; Grin & van der Veen, 1950; Scharroo, 1946; Van der Schrier, 1938, 1942, 1953, 1960, 1968). More recently, plastic spacers were applied (Van der Schrier, 1968). Occasionally, concrete spacers made from copper were used (Figure 6.45).

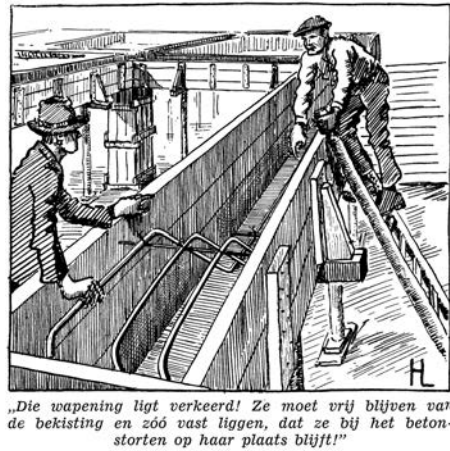


Figure 6.43 Illustrative drawing of misplacing the reinforcement *“The reinforcement is placed wrongly! It has to be free from the formwork and lying firm so it remains on its place during the pouring of the concrete!”* (Scharroo, 1929, p. 21).

Less reliable and discouraged techniques were the use of gravel as spacers, which due to size variations could not guarantee a consistent thickness, or the placing of small pieces of reinforcement bars under the reinforcement, which caused rust stains on the surface and could lead to corrosion of the reinforcement at these locations (Grin & van der Veen, 1950; Van der Schrier, 1938, 1942, 1957, 1968). For exposed concrete, the use of spacers made from concrete was discouraged, since they absorb water from the concrete and could change the colour of the concrete. Instead, spacers made from stainless steel or plastic with a spherical or conical shape were advised, which had only little contact with the surface (CUR report 36,1966). The use of spacers to secure the minimum thickness of the concrete cover was first mentioned in the G.B.V. 1930, advising to use watertight concrete blocks, and excluding the use of iron spacers for exterior elements and watertight structures. The use of iron/steel spacers was generally forbidden in the G.B.V. 1950. According to the G.B.V. 1962, the spacers must be made from concrete or an equivalent material, and, for the first time, the use of spacers for vertical elements is mentioned.

Besides the thicknesses indicated in the respective G.B.V., historic documents such as construction drawings or project descriptions can give a first indication of the intended thickness of the concrete cover. Yet attention has to be given whether the information refers to the main reinforcement, secondary reinforcement or even to the distance from the surface to the centre of the reinforcement bar, later used for calculation. For example, Van Hemert described the distance of the reinforcement to the bottom of the beam used for testing as 2.14 cm; in the accompanying Figure 6.46, it can be seen that the value refers to the centre of the rebar, resulting in a concrete cover of only 8.8 mm (Van Hemert, 1901).

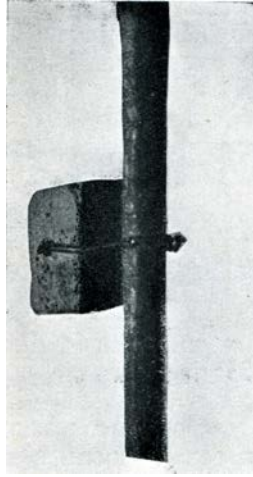


Figure 6.44 Picture of an early concrete spacer (Boon, 1931, p. 126).

Compared to the present required minimum concrete cover, the cover of historic concrete buildings can be too thin and not designed appropriately to the exposure class. The latter can apply for the concrete mix as well (e.g. cement content, water/cement factor). Therefore, historic concrete structures can, in some cases, be more prone to reinforcement corrosion, especially if the quality of the cover is poorer (for example voids and cracks). Due to the age of the structures the carbonation front can be deeper as well.

To be able to estimate the possible thickness of the cover concrete on-site and to calibrate a cover meter, it is necessary to know which elements can be encountered in reinforced concrete structure besides the main reinforcement. The reinforcement was initially differentiated in a theoretical reinforcement, which was dimensioned according to the load case, and a practical reinforcement, which included the shrinkage reinforcement and the distribution reinforcement (*verdeel wapening*). The practical reinforcement is usually perpendicular to the main and load bearing reinforcement (Dwars, 1912). A distribution reinforcement was required in the G.B.V. 1912 for slabs of at least 20% of the main reinforcement. Its design was solely empirically based as it was not possible to calculate it. A shrinkage reinforcement was applied on the exterior side of elements which were exposed to the elements or to high temperatures (Dwars, 1923). For columns and beams, stirrups were applied; in case of Hennebique structures, these were commonly strips, otherwise plain bars were used.

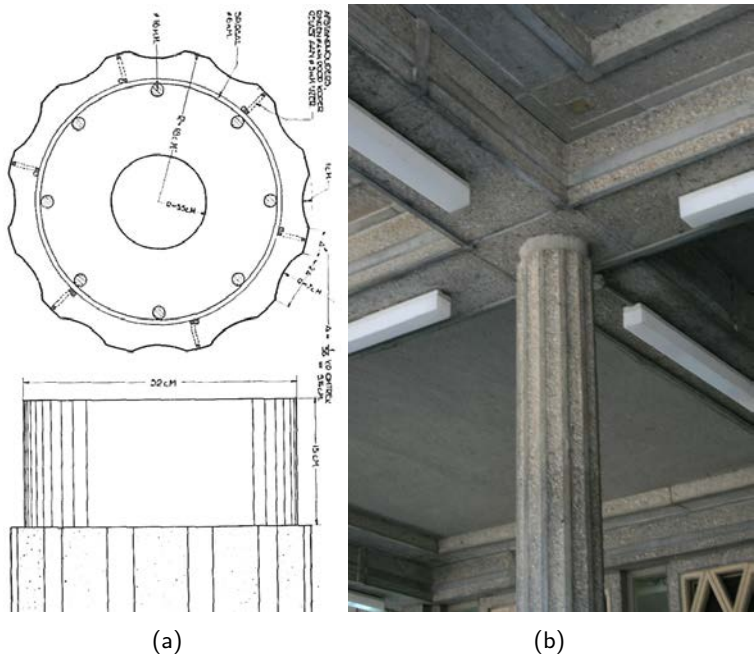


Figure 6.45 Example of the copper concrete spacer, welded to the reinforcement (railway station Enschede, H.G.J. Schelling, 1950). a) Section through the column showing the reinforcement and the spacers (Schelling, 1950b, p. 738). b) Picture of the resp. column, situation 2009.

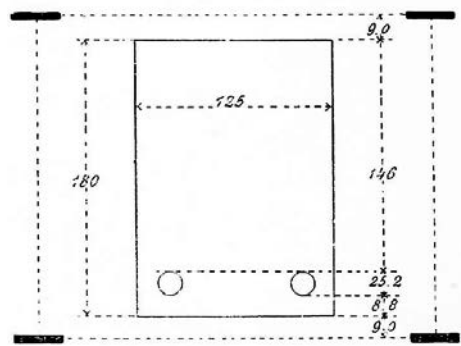


Figure 6.46 Overview drawing of testing beam (Van Hemert, 1901, appendix 3)

6.6 Conclusions

In this chapter it was shown that reinforcement used for historic concrete in the Netherlands underwent several changes. The changes affecting the iron and steel industry in the first half of the 20th century influenced the reinforcement in terms of material composition, terminology and standardisation. Regarding the terminology for iron and steel, attention has to be given to historical context and linguistic context, as the Dutch (and Germanic) situation is not identical to the French and English context.

Concerning the typology of reinforcement systems, a wide variety can be encountered. Yet, contrary to other countries, patented reinforcement bars played a minor role in the Netherlands. During time, a simplification of reinforcement types can be encountered, reflecting economic aspects and scientific insight. With the increased understanding of durability, the design of the reinforcement, especially its location was modified and the concrete cover increased.

Different positions, reinforcement elements and connection methods were identified which are relevant for inspections (for example cover metre, measuring of resistance), as these could influence obtained values. For the identification of the used reinforcement system, not only is it advisable to gather information from historic documents and the historical context (Figure 2.16 *Timeline for the reinforcement used for historic concrete*), but also from site visits, as the reinforcement is often exposed when deterioration has occurred. Correct identification is relevant for both structural recalculations and the evaluation of different conservation strategies and heritage values.

Due to the recentness of the field, little data is available of the influence of the metallurgical differences of historic *ijzer* (iron) used as reinforcement, data which might be relevant when estimating the propagation of present damage and considering the desire to preserve the original material as long as possible.

Chapter 7

The surface finish of historic concrete

Chapter Outline

In the previous Chapters 2 to 6, different constituents used in historic concrete and their mix design were addressed. In this chapter, the surface finishes of historic concrete will be discussed. Their development and sophistication is in close relationship with the previously mentioned advances in concrete technology and social acceptance of concrete. After a historical overview, including the social acceptance, different techniques to alter the appearance of concrete will be discussed. Some of these are still in use today, whereas others are unique in the history of concrete surface finishes. Other aspects are special constituents to alter the colour of the concrete.

7.1 Introduction

The surface finish of historic concrete is important in many ways. One of the most relevant aspects is its role in the appearance of the building, and thereby influencing possible heritage values. As many historic concrete surfaces have been covered (e.g. painted, rendered, cladded) during time, the original surface cannot always be identified directly, requiring further investigation. Additionally, the historical development of concrete surface finishes is not known, hindering the identification of possible original surfaces.

Technically, the quality of the surface finish influences the durability of the concrete. Some techniques can enhance it, whereas others can decrease it. The surface itself is also affected by most damage mechanisms as they can for example lead to cracking or spalling. In case of repair, it is essential to identify the encountered surface finish, the used techniques and constituents in order to choose a technically

and aesthetically compatible intervention. Therefore, the surface finishes applied to historic concrete in the Netherlands will be the scope of this chapter.

Initially, a discussion of how to aesthetically treat the surface of concrete was not necessary, as the concrete was not left exposed and mainly used for structural elements (see also Section 2.2 *Historical context*). With the increasing civil and architectural use of concrete at the end of the 19th century, its aesthetical possibilities were explored and appropriate surface finishes were searched for. Reviewing the surface finishes applied to historic concrete in the Netherlands, foreign influences from Germany, the United States of America and France can be identified. Some national, specific applications and techniques can be encountered as well, such as the Dutch patent for the metallisation for concrete.

To illustrate the variety of historic concrete surface finishes applied in the Netherlands, this chapter will give a historical overview of concrete surface finishes, explaining the changing appreciation and application. The use of special constituents to improve the appearance of the normally grey concrete will be discussed. The role of the technological development and scientific insight will be commented. Together with the insight from the previous chapters, the specific properties of different surface finishes will be explained.

Concerning the historical development of the surface finish of historic concrete, several misconceptions exist. It is commonly assumed that exposed concrete was only accepted for architecture in the Post-war years and is often associated with architectural styles, such as the Brutalism and with individual architects, in particular Le Corbusier (1887-1965). Fine architecture dating before this period is often assumed to be either plastered or painted (see for example De Jonge, 2006). This might be applicable for some architectural movements where concrete did play a major role, such as the Modern Movement, where concrete was widely used but plastered (see for example Figures 1.1 and 1.2).

For industrial buildings, it is often assumed that the surface was left untreated in the early years, showing the raw imprint of the timber formwork. Although exposed concrete can be found much earlier in industrial buildings than in fine architecture (often due to economical reasons), the aesthetical quality of the surface exposed to the public was considered for industrial buildings (e.g. street façades, or interior elements). For example, the interior concrete columns of the recently refurbished Lichttoren of the former Philips factory in Eindhoven were originally plastered (der Hoeve & Kamphuis, 2000). During the intervention, the plaster was removed with the idea to create a “chic, industrial” loft atmosphere following a “brute material romantic one” attributed to (industrial) concrete buildings (Figure 7.1). The now exposed concrete is shown with all blemishes such as voids and exposed reinforcement (see also Figure 6.37b), which would have not been accepted in interior rooms at the time of construction. The columns were painted in “concrete grey”, an originally disliked colour, for protection and to limit the amount of dust for the users. Although this is now sold as an “authentic industrial loft-look”, it is far away from the authentic situation.

Misconceptions also exist with respect to the period of application of coloured



Figure 7.1 Example of the “romantic and brute industrial atmosphere” of the interior of concrete buildings (*Lichttoren*, Philips building ED, Eindhoven; Bureau TABROS1920/21, situation during intervention 2007).



Figure 7.2 Façade of a reinforced concrete building, combined use of artificial stone and *kunstzandsteenpleister* (artificial sandstone render, former hotel-restaurant “De Twee Steden”, The Hague, Joh. Mutters Jr, 1904-1906, situation 2010).



Figure 7.3 Prefabricated coloured concrete elements; due to local damage it can be seen that the material is concrete and not a render (Riveràhal of the Zoo Blijdorp, Rotterdam, van Ravesteyn, 1939-1941, situation 2011).



Figure 7.4 The original material of the column and arch is tuff stone, only local replacements were carried out in well-made natural stone imitations (top of the column) (Faculty of Architecture, former Faculty of Chemistry, TU Delft, G. van Drecht, 1918-1923, situation 2011).

concrete; its use prior to the Second World War is often not considered or even recognised. Instead, reinforced concrete with a jointless *kunstzandsteen* render (artificial sandstone render) and artificial stone are mistaken for natural stone (Figure 7.2), coloured concrete for a rendered concrete (Figure 7.3); opposite mistakes happen as well and natural stone, in this case a tuff stone, is identified as *kunststeen* (artificial stone, Figure 7.4, for example RCE 1993; 2002b; 2008).

Regarding appropriate surface finishes for concrete, not only style and aesthetics influenced the choice; other factors were building typology (for example infrastructure, military, industrial, fine architecture), the type of construction (pre-fab or in-situ) or the intention for using concrete (e.g. substitute for natural stone, load bearing material). According to Van der Schrier (1938), three reasons for treating the surface of concrete existed: first, to protect the concrete from the elements, second to prevent concrete (floors) from wear and tear, third, to make the concrete surface prettier; for walls, three categories of surface finishes were discussed: applying a plaster after hardening, a treatment while pouring the concrete and a treatment of the hardened surface to emphasise the texture of the concrete.

Reviewing historic concrete literature, one can notice that the appearance of concrete was always discussed from the end of the 19th century onwards, and not only in terms of disguising the concrete. When looking closely at the concrete heritage, it is noticeable that several types of surface finishes have been used. Most techniques applied had been already developed at the beginning of the 20th century. Some of these are still common, others have been technically improved, some have been forgotten and others recently “reinvented”. Some techniques addressed both durability and aesthetics such as metallisation (Section 7.3.6), which was advertised for its beneficial side effect of improving the durability of concrete.

The way historic concrete was modified to fulfill the aesthetical demands of its time, can influence its durability, both positively and negatively. In the previous chapters the influence of the different constituents, design details (e.g. concrete cover) and the quality of the concrete surface (e.g. density) on the overall concrete quality and durability have already been discussed. A good surface can prevent or reduce the ingress of harmful agents (e.g. CO₂, H₂O, salts). For example, negative effects could have been caused by using new pigments without understanding their long-term effects, tooling could have reduced the thickness of the concrete cover; for facing concrete and decorative concrete, different concretes made with different concrete mix designs were combined, possibly causing damage at the interface between the different concretes.

With increasing quality demands towards exposed concrete, more attention was given to the concrete mix and construction. The quality improved as pre-fabrication was used more commonly for coloured concrete, especially during the reconstruction period after the Second World War; the compaction of concrete was better allowing the use of a lower water-cement ratio, combined with a better quality control. The urge to increase the production speed of prefabricated elements led to the use of accelerators and steam curing, techniques which are now known to cause premature material failure.

After a historical overview of the development of concrete surface finishes in Section 7.2, the different techniques will be discussed in detail in this chapter.

7.2 The development of concrete surface finishes

In the late 19th century, the use of concrete was mainly limited to structural elements such as columns, vaults, and floors, later also to walls. Concrete was commonly disguised either by plastering or by cladding with other, traditional materials (e.g. bricks, natural stone, see Figure 7.5). Therefore, an aesthetical treatment of concrete surfaces was not relevant. An exception was the use of concrete as natural stone imitations, known in Dutch as *cementsteen* or *kunststeen*. The colour and texture of the concrete was modified to match the appearance of the stone to be imitated (Stokroos, 1985). This was done by using special coloured constituents and by tooling the surface. Good examples are the products of the company *Rotterdamsche Cementsteenfabriek Van Waning & Co* (Figure 7.6). In Germany, for example, an entire *Kunststein* (artificial stone) industry existed, with several recipes for imitating different natural stones from initially sand stones to later a wider variety of natural stone such as grey wacke, porphyry, tuff, sandstone, limestone and granite (Probst, 1919).

With the increased use of concrete at the beginning of the 20th century, a growing interest to find an appropriate concrete architecture and surface treatment can be observed internationally (Collins, 1959; Onderdonk, 1928; Petry, 1913; Von Mecenseffy, 1911). In his book about the aesthetical treatment of concrete, Petry (1913) wrote about the successful application of concrete as an aesthetical material in Germany, showing that it is not necessary to hide concrete behind plasters or claddings. A promising, concrete specific technique was the use of facing concrete, where a thin, visible layer of coloured concrete was poured together with a cheaper normal backing concrete (see Section 7.6); this technique had already been applied on a wide scale in Germany. In Dutch textbooks, reference was often made to other advanced techniques used in Germany, such as applying and tooling of plasters made with ground natural stone, or sand blasting of concrete (Bergsma & Homan van der Heide, 1910b; Boon, 1913, 1920; Scharroo, 1921; Verhey, 1912).

In the Netherlands, an architectural use of concrete was relatively late. As the architect J. Gratama (1877-1947) judged, construction with reinforced concrete could not be called “*bouwkunst*” yet (Gratama, 1912).¹ Dutch architects were still waiting what this new material could offer (Bergsma & Homan van der Heide, 1910b; Gratama, 1912). Most architects were considered conservative and did not know enough about this new material to be able to use it for architectural purposes. The leading role was left to civil engineers, who knew how to take advantage of reinforced concrete for infrastructure and military buildings. An own architectural concrete language was still missing and concrete buildings imitated

¹ *Bouwkunst* is a Dutch term for architecture, literally meaning “building art”.



(a)



(b)

Figure 7.5 Two early reinforced concrete buildings with façades made from traditional materials. a) One of the earliest Dutch examples using reinforced concrete slabs (Sanders, 1907) which is not noticeable from the façade made from brick and sandstone (Former bank building Rijkspostspaarbank, Amsterdam, D. E. C. Knuttel, 1899–1901, situation 2011). b) Reinforced concrete frame clad with natural stone (Rakovice sandstone for the main building, Ettringer tuff for the tower, Town hall Rotterdam, H.J. Evers and A.J.Th. Kok, 1914–1920, situation 2009).



(a)



(b)

Figure 7.6 Natural stone imitation used in the former headquarters of the *Rotterdamsche Cementsteenfabriek Van Waning & Co* (Rotterdam, J. I. van Waning 1898, situation 2010). a) Façade with advertisement made in artificial stone; the artificial stone has been painted. b) On the side the original texture and colour of the artificial stone is locally still visible.

the look of buildings constructed in traditional materials. It was assumed that a specific concrete style would develop with its own form and beauty. A transition towards a concrete (surface) style could be already observed at the beginning of the 20th century. For example, the joints of a natural stone façade were not imitated anymore when tooling concrete surfaces (Figure 7.7), resembling more the seamless structure of monolithic concrete structures (Gratama, 1912). Besides the surface finish, the finer proportions of bearing elements possible with reinforced concrete questioned the traditional ideas on aesthetics (Rutgers, 1909).

An aesthetical problem was the grey colour of concrete, which was generally not appreciated and traditional materials such as brick or natural stone considered prettier. The grey concrete was considered as dull and lifeless (Boon, 1908; Verhey, 1912), and it generally had a lack of character (Rutgers, 1909). The architect Van Loghem (1918) even went a step further and stated that it was of all things this grey non-colour which degraded concrete to a functional material, and only colour could express beauty; as concrete was the result of intellectual achievements and a manufactured material - using artificial constituents as cement and iron - it required a sufficiently intellectual aesthetical surface finish which must be coloured; Van Loghem saw the solution in metallisation, a newly development method which artificially changed the colour of concrete (Section 7.3.6).

Existing civil engineering structures showed that an aesthetically satisfying use of concrete was possible; however, these solutions were not considered yet as sufficient for architecture (for example Boon, 1908; Gratama, 1916; Scharroo, 1946). Leaving the surface untreated and accepting the randomness of the formwork was possible for industrial buildings in the early years, yet for the fine architecture such surface finishes were only accepted on a large scale in the Post-war period. Common yet problematic methods were to render (Section 7.3.1) or paint (see Section 7.3.2) concrete.

An own concrete architectural style together with material specific surface finishes was searched for. To alter the disliked grey colour of concrete, most early applied surface finishes techniques removed the grey cement film to expose the aggregates (Sections 7.3.3 and 7.3.4), sometimes in combination with the use of coloured cement and coloured aggregates (see Section 7.5). A wide exploration of surface finishes can be found in early infrastructures, such as bridges and viaducts, as, due to their scale and often urban location, they required an aesthetical appearance of the concrete.

In the Interwar period, two main tendencies can be observed for the surface finish of concrete: on the one hand a rendering of concrete buildings, such as it is now associated with buildings from the Modern Movement (Figure 1.5 and 2.11); these buildings are often described as *“plain white boxes [...] constructed out of concrete or concrete block with stucco [...] with [...] lack of ornament”* (Prudon, 2008, pp. 3-4). On the other hand, an exploration of the possibilities of coloured and tooled concrete took place (Figure 2.11b). A development of this time is decorative concrete (Section 7.7), which combined several surface finish techniques and a conscious choice of constituents. A variety of techniques to treat



(a)



(b)

Figure 7.7 Two examples of reinforced concrete structures rendered with *kunstzandsteenplaster*, imitating the appearance of a tooled sandstone façade. a) With the imitation of joints (St. Jobsveen Rotterdam, J.J. Kanter, 1912, situation 2010, showing local repairs). b) Without imitating joints (Hofplein railway viaduct, Rotterdam, A. C. G. van Hemert, 1900-1908, situation 2009, original surface painted).

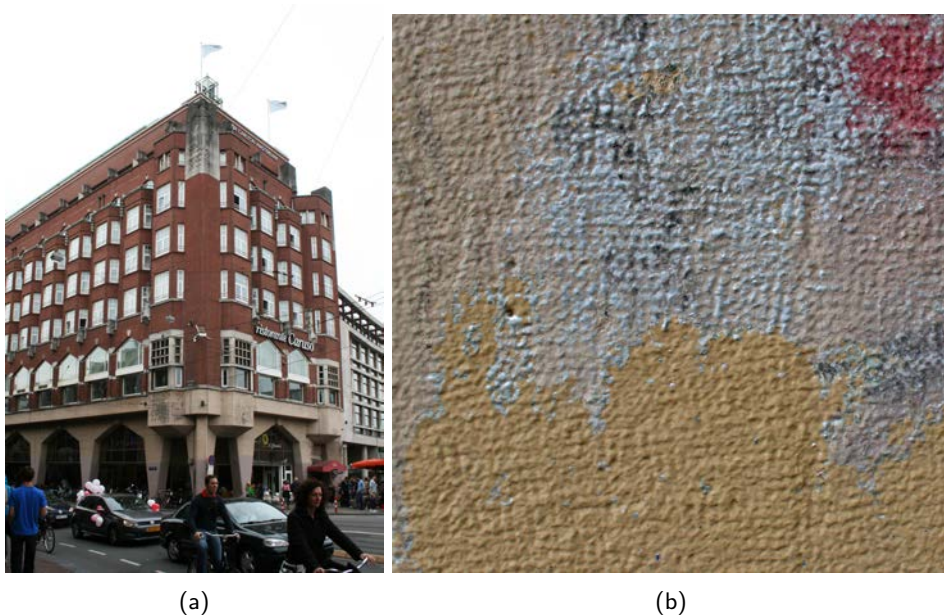


Figure 7.8 Large scale architectural application of exposed, bush hammered concrete (former *Grand Hotel*, Amsterdam, G. J. Rutgers, G. van Arkel and H.J. Breman, 1925-1929, situation 2010). a) Overview building with originally exposed concrete arcades, currently painted. b) Detail showing the texture caused by bush hammering, the original colour is not visible due to layers of paints and graffiti.

the surface of concrete had been applied in this period: rendering, sometimes by using a decorative render, tooling, brushing, polishing, use of coloured cement, and metallisation (Scharroo, 1940, 1946).

The discussion whether concrete should be left exposed on a large scale or not still continued, and sometimes plans changed. For example, the concrete structure of the *Grand Hotel* in Amsterdam (Figure 7.8), was designed to be clad with bricks and Bavarian granite (Mieras, 1925), but executed with a exposed, bush hammered concrete. Only smaller elements such as the plinths of the column were clad with granite and bush hammered in the same style as the concrete. In other cases, the concrete was intended to be exposed and carried out as such. For example, the Olympic stadium in Amsterdam by J. Wils (1927, see Figure 7.9) was designed as a combination of exposed concrete and exposed brick work (Scharroo & Wils, 1927). Yet, the current status of the stadium is representative for many exposed concrete buildings of this period; the concrete is commonly painted either white or “concrete grey”, without considering the originally intended vivid colour of the concrete, and repairs are neither adapted in texture nor colour, misleading our present-day conception of exposed concrete in the Interwar period. The painting of exposed historic concrete is not always a conscious choice made during a restoration

campaign but an uncritical or pragmatic perpetuation of previous interventions.

In this period, achieving a good exposed concrete was still limited by the state-of-the-art of concrete technology. Different techniques were criticised for their quality (e.g. visible formwork imprints), durability (e.g. detachment of plasters, removal of the cement film) and maintenance (painting) (Wattjes, 1931). Publications addressed the technical aspects for achieving a good concrete surface and how to avoid blemishes (for example Roelofsen, 1940). The architectural discussion on if and how far the concrete should be left visible went on; for example, Wattjes (1927) negatively described the exposed, sand blasted concrete frame of the office building *De Nederlanden van 1845* by Hendrik Petrus Berlage (1856-1934) and hoped that such architecture would not become common (see Figure 7.10a). Social issues were occasionally the force behind using concrete, as for example for the high demand for social housing after the First World War (Kuipers, 1987). Yet, these large scale housing projects were sometimes plastered (see Figure 7.10b).

Although more commonly applied during and after the Second World War, concrete was not always the material of first choice. Due to the material scarcity in this period, concrete sometimes was chosen as a substitute for natural stone. For example, the sculptures by L. Boole in the *Zoo Blijdorp* (Figure 7.11) were made in decorative concrete due to a lack of money (De Vries, 1986). The situation after the Second World War with the need for quick, cheap reconstruction and lack of traditional building materials and of skilled workers, favoured the use of concrete.

Concrete had become a more reliable material; the experimental years of this new technique had passed, and knowledge about concrete was well disseminated. A reliable construction of exposed concrete was possible due to the existing infrastructure for the production and construction of concrete buildings. This made a good quality of the concrete surface possible, which strongly depends on the level of workmanship and material. Especially the development of better compaction methods, including *schokken* of prefabricated elements, improved the quality of the concrete surface (Schelling, 1950b). The economic benefits when using exposed concrete compared to rendered walls increased its use (Scharroo, 1951). The lack of timber for formwork supported the use of prefabricated elements as a permanent formwork (Figure 7.12, see also Schelling, 1950a,b, 1952b).

The perception of concrete had changed, too. Mieras described as if concrete architecture had freed itself from the brick tradition of the 19th century, and now it was possible to build a concrete architecture, which needed no disguise (Mieras, 1950). However, compared to other countries, the situation was comparable to the beginning of the 20th century and Mieras criticised that the Dutch lagged behind when it came to the appearance and form of reinforced concrete buildings. Causes were seen in the Dutch tradition and preference for brick, as exemplified by the still well-known exhibition *Nederland bouwt in baksteen* (Netherlands builds in brick) in Museum Boymans-Van Beuningen in 1941, and concrete still considered as less noble (Mieras, 1954). The works of the Dutch railway architect Schelling, which were inspired by the works of the French Auguste Perret (1874-1954) and the Swiss Denis Honegger (1907-1981) were considered as an exception, and even

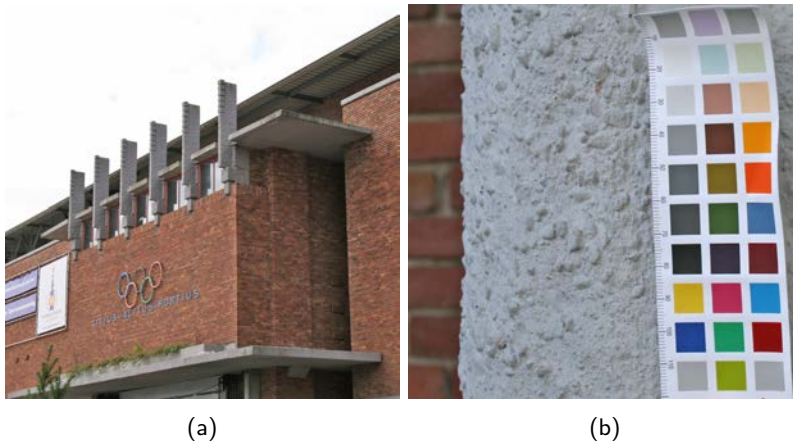


Figure 7.9 Combination of brick, natural stone and exposed concrete. The texture and colour of the concrete was changed by either sand blasting or washing out, yet has been painted later “concrete grey” (exact date of 1st painting unknown, large scale restoration carried out in 1999); exactly the colour that was desperately tried to be avoided in the 1920s (Olympic stadium Amsterdam, J. Wils, 1927, situation 2008). a) Detail entrance façade. b) Detail column; due to the grey paint the colour variations caused by the aggregates are not visible anymore.

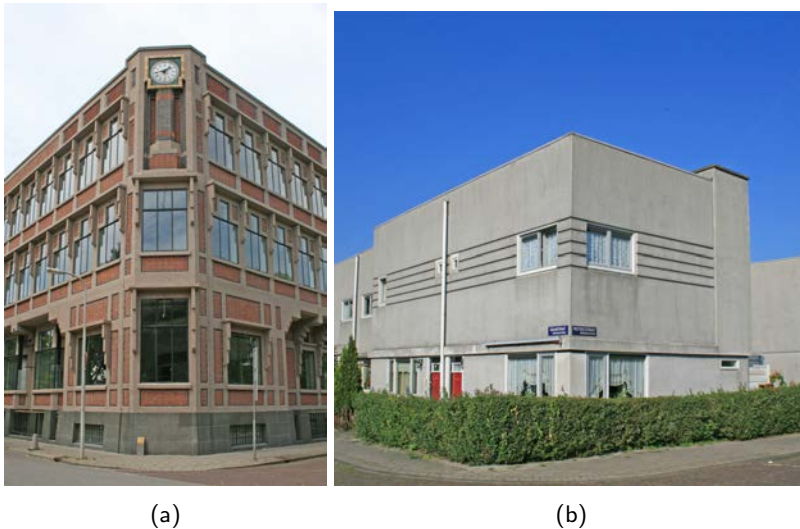


Figure 7.10 Two examples of innovative application of concrete in the 1920s. a) Use of visible concrete frame for an office building, originally with a sand blasted surface which is currently covered (office building De Nederlanden van 1845, The Hague, H.P. Berlage; 1921-27/ extension 1954 by Dudok, situation 2009). b) Wide scale application of concrete for social housing, façades mainly rendered (*Housing Betondorp*, div. architects. 1918 -1928, situation 2008, current renders date from renovation campaigns, often a thermal insulation composite system).



Figure 7.11 Example of use of decorative concrete instead of natural stone for sculptures due to material scarcity (Main entrance Zoo Blijdorp, Rotterdam, S. van Ravesteyn, sculptures L. Bolle, 1939-1941).



Figure 7.12 Overview of the Railway station Enschede; the beams were made with permanent formwork (Schokbeton) due to timber scarcity after the Second World War (H.G.J. Schelling, 1950, situation 2009, see also Figure 6.45).

mentioned abroad (Collins, 1959; Evers, 1958; Mieras, 1950). Schelling (1950b) stated that concrete should not be ashamed of its origin, and not be used anymore to imitate natural stone. He rejected all the ideas of *sierbeton* (decorative concrete) or *kunststeen* (artificial stone) and associated euphemisms. Concrete was a worthy material by itself; it should never be covered or plastered. The constituents, binder and aggregates should be visible and only pigments could be used to alter the colour.

Yet Schelling's works were not considered by Mieras as real reinforced concrete architecture, since the appearance of the concrete was too modified (Mieras, 1954). Instead, two exposed concrete churches (Sint Joseph church in Amsterdam by G.H.M. Holt and K.P. Tholens, and Sint Anna church in Heerlen by F.P.J. Peutz), where the exposed concrete even showed the formwork imprints, were considered as Dutch examples of good reinforced concrete architecture. The Sint Joseph church in Amsterdam was welcomed, as with it the Dutch finally had a concrete church and could compete now with other countries in terms of concrete architecture (Van der Schrier, 1952). Good reinforced concrete architecture was seen in the Post-War architecture by Le Corbusier and his *Unité d'Habitation*; works inspired by this concrete architecture can be found in the Netherlands. For example, the school building of the former *Eerste Christelijke LTS Patrimonium* (Figure 7.13a) shows both in form and surface finish such influences. The architectural firm Van der Broek & Bakema were seen as Dutch examples for "concrete architects" and their auditorium of the Technical University of Delft, planned in the 1950s, (Figure 7.13b) considered as a milestone in Dutch concrete architecture (Luning Prak, 1967).

Scharroo (1951) remarked that concrete should neither be anymore seen as a sole bearing material - so to say the skeleton of a building - nor hidden, and the true character of the plain appearance of concrete appreciated. Concrete was suddenly praised and even described as romantic, since it possessed an own distinct beauty and like no other stone-like material it could adapt to its environment in terms of patina (Fernhout, 1957). Yet the normal, grey appearance of concrete was still discussed, and similar concerns expressed as at the beginning of the 20th century of how to avoid the "dead" and grey, dull surface (Roelofsen, 1950).

A result was the increase use of coloured concrete. As the making of coloured concrete on-site was difficult, coloured concrete elements were commonly prefabricated. A wide variety of prefabricated decorative concrete elements appeared on the market for all purposes (Bond van Fabrikanten van Betonwaren in Nederland, 1957, 1964; Bonnema & Vegter, 1946; Fernhout, 1957). Traditional surface finishes such as tooling and polishing were still applied, but new types of formwork allowed the economic construction of both smooth and textured concrete surfaces (Scharroo, 1951).

In parallel, the grey colour of normal concrete became more and more accepted, questioning the need to change its colour (for example Scharroo, 1940). The advanced acceptance of concrete as an aesthetically worthy and sculptural material is reflected in its increased use for public art. Especially in Post-War public



(a)



(b)

Figure 7.13 Two examples of exposed concrete buildings which were considered to be of a high quality. a) Former *LTS Patrimonium* school (Amsterdam, J.B. Ingwersen, C. de Geus and C. v.d. Bom, 1952-1956, situation 2011). b) Auditorium TU Delft (architectural firm van de Broek & Bakema, 1959-66).



(a)



(b)

Figure 7.14 Reinforced concrete sculpture in front of the Olympic stadium in Amsterdam by F. Carasso (1947, situation 2007). a) Overview. b) Closeup showing eroded surface texture.

buildings, several pieces of art made from or with concrete can be encountered, either as sculptures or integrated in walls as mosaics (see Figures 7.14 to 7.19).

Yet the incapability of the Dutch to achieve a consistent good quality of exposed concrete, and its low quality compared to the high quality achieved in other countries such as Denmark, Sweden, Finland or France, questioned the future of exposed concrete in the Netherlands. The painting of the *Groothandelsgebouw* (Figure 7.20) in Rotterdam was hereby mentioned as an example of the questionable ageing of exposed concrete (Luning Prak, 1967). With the increasing insight into durability, and the signs of deterioration that many elder structures started to show, doubts were expressed whether it was technically possible to leave concrete exposed. A discussion was carried out in the Dutch journal *Bouw* (Arensohn, 1953; Rosema, 1953), where signs of corrosion and spalling supported the prejudices of not using exposed concrete, whereas several older buildings with no signs of damage proved that it could be possible.

A good concrete surface depends on planning, materials, and construction. Considering the history of concrete, sufficient time needed to elapse for the construction methods to improve. This did not only depend on technological development, but on the entire construction process as blemishes (e.g. voids, segregation, colour variations) are visible on exposed concrete surfaces. The quality depended on concrete mix design (e.g. grading, water content), mixing, construction (formwork), compaction (internal vibrators), and curing of the concrete. Many of these tools and skills were only available on a wide scale after the Second World War (CUR report 36, 1966; Gray & Childe, 1943; Scharroo, 1951).

With the increased use of exposed concrete, regulations were adapted, as the importance of the concrete surface was understood better and with it the influence of the surface finish on the durability of concrete (e.g. removal of the cement film). For example, tooling of the surface reduces the concrete cover. Technical literature already advised an increased concrete cover when tooling the surface in the 1930s. Bergsma (1934) advised 2.5 cm to 3.0 cm remaining concrete cover after bush hammering, Roelofsen (1940) an original cover of 3.5 cm before bush hammering. Besides reducing the concrete cover, tooling could cause micro cracks, through which harmful agents could ingress. Technical publications such as the CUR report 36 *Fair-faced concrete* (1966) discuss the technical details of planning and construction of exposed concrete.

The aesthetical qualities of exposed concrete were not addressed in the *Ge-wapend Betonvoorschriften* (G.B.V., Netherlands Code of Practice for Reinforced Concrete), but only the consequences of a surface finish for the thickness of the concrete cover (see Section 6.5). To compensate the loss of concrete cover, an increased thickness of the cover concrete when tooling the surface was required for the first in the G.B.V. 1940. In the G.B.V. 1962, the types of surface techniques which affect the concrete cover were mentioned: tooling, sand or grit blasting, and washing out with diluted acids (see also Table 6.3).



Figure 7.15 “Drawings” made in decorative concrete elements, produced by the Dutch company De Metoor (Grotius high school, The Hague, Sj. Schamhart, “drawings” by W.J. Rozendaal, 1949-1955, situation 2006). a) Overview entrance. b) Detail showing the use of different coloured concrete in one element and tooled surface.



Figure 7.16 Reliefs by B. Guntenaar at the entrance of the railway station Zutphen (H.G.J. Schelling, 1952, situation 2009).



Figure 7.17 Prefabricated concrete elements with a mosaic by L. van Roode (Holbeinhuis, Rotterdam, E.H.A. & H. M. Kraaijvanger, 1953, situation 2009).

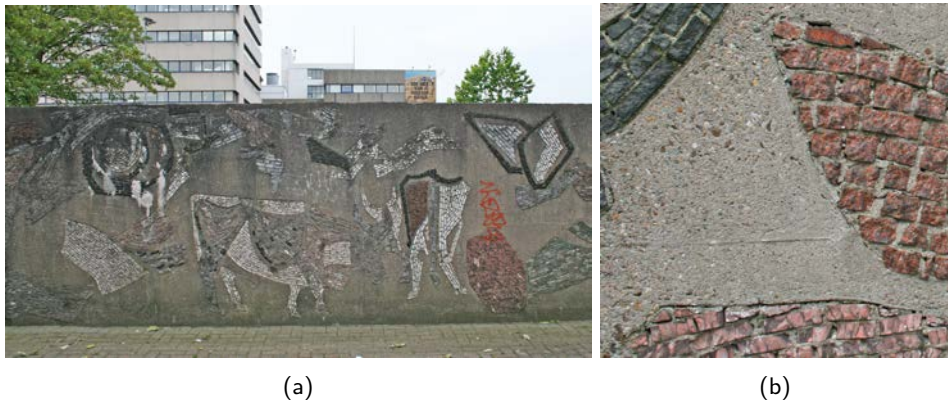


Figure 7.18 On-site concrete wall with mosaic (marble inlay) designed by H. op de Laak (former LTS Patrimonium school, Amsterdam, J.B. Ingwersen, C. de Geus and C. v.d. Bom, 1952-1956, situation 2011). a) Overview. b) Detail; the sharp edges between the in-situ concrete and the area of the mosaic, together with the difference in mortar and surface depth indicate that the mosaics were placed after pouring.

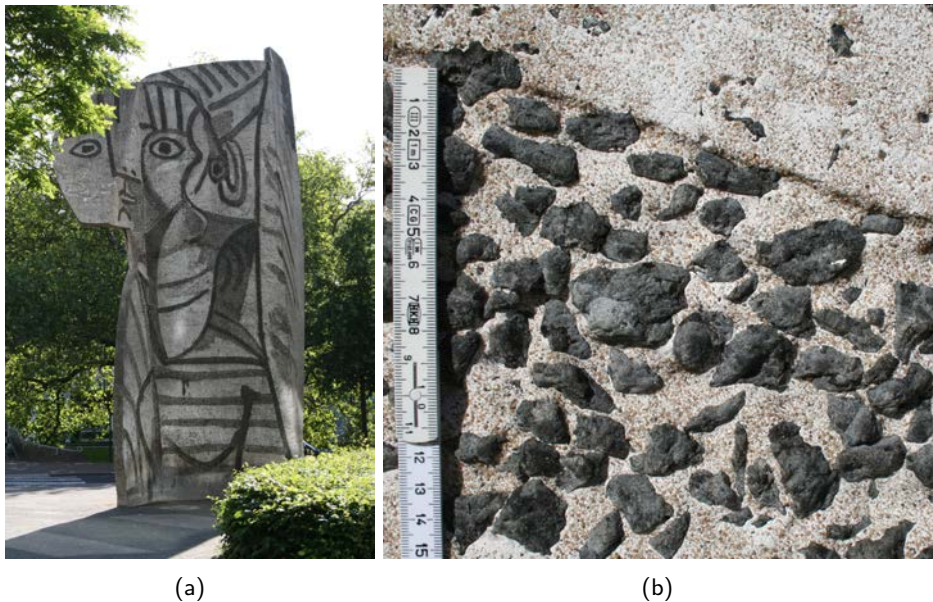


Figure 7.19 Sculpture made in reinforced concrete (Sylvette, Rotterdam, P. Picasso, 1970, situation 2010). a) Overview. b) Detail showing that the lines on the sculpture were made by exposing a darker aggregate and the use of white cement.



Figure 7.20 The office building *Groothandelsgebouw* is an example of combining pre-fabrication with different surfaces finishes. The building was painted white to cover up repairs in the 1960s. During large scale restoration works in 2001-2005 the paint was removed; degradation problems are still present (Rotterdam, H. Maaskant & W. van Tijen, 1950).

7.3 Surface finishes applied to historic concrete

The origin of the earliest techniques used for concrete surfaces finishes can be found in the treatment of natural stone and terrazzo. For example, techniques and patterns for tooling have their origin in the treatment of natural stone, polishing and use of coloured aggregates in terrazzo. The wide-scale fabrication of natural stone imitations supported the use of special constituents and tooling. Surface finishes which are now commonly associated with exposed concrete, such as formwork imprints, took time to be technically perfected and to be aesthetically accepted. Painting and rendering were known as general surface finishes, yet were not easily applicable on concrete surfaces as the alkalinity of fresh concrete caused a saponification of oil-based paints and renders detached commonly.

The surface finish of concrete can be altered in different phases of the construction process: design of the concrete mix (for example use of coloured constituents, grading), during construction by choosing special formworks or after the concrete has hardened (e.g. exposing the aggregate, plastering, metallisation). In the following sections, the techniques applied to modify the surface of historic concrete in the Netherlands will be discussed; they are selected, as they are common for historic concrete (quantity), seldom or forgotten (rarity) or their history misunderstood. Some techniques which became more common after the 1960s, such as aggregate transfer, are not discussed as they are outside of the period discussed in this thesis. Some other techniques, such as sgraffito were applied on historic concrete, especially in the Post-war period, yet are technically more a variation of

a plaster technique than a specific concrete surface finish (see for example Op de Laak, 1957) and therefore neither addressed.

7.3.1 Rendering

The surface of historic concrete was rendered to improve its watertightness, to smoothen the surface or, in the case of decorative plasters, to improve aesthetics. The render applied on the concrete surface was often based on Portland cement. In case the concrete was made with a different binder than Portland cement, for example with some parts of lime, it was advised to make the render using the same binder as used for the concrete (Minister van Oorlog, 1906). For early concrete military buildings (for example Figure 7.21), the advised mixtures for renders were based on a cement mortar with 1 part Portland cement with one part sand, this mixture was known as C.2; or a Portland cement-lime mortar, known as C.K. 3, made with 1 part lime (made from shell lime or lime stone), 1 part Portland cement and 3 parts sand (Minister van Oorlog, 1906).

A leaner mortar mix for plasters was advised by Van der Kloes (1893) to make tampered concrete structures watertight, containing 1 part Portland cement and $2 - 2\frac{1}{5}$ parts of sand; to improve the workability Van der Kloes recommended to add 10% of lime in form of lime solution (*kalkmelk*). Later recipes for renders for concrete surfaces varied between 1 part of cement and $1\frac{1}{2} - 3$ parts sand; in case the render should be white, lime from the Belgian city of Tournai (*Doorniksche kalk*) was advised. However, the adhesion of a lime based render was weaker, therefore a thin layer of mortar made from Portland cement had to be applied first (Boon, 1913, 1920; Scharroo, 1916, 1921; Van der Schrier, 1938; Verhey, 1912). The use of a lime based render is later discouraged for exterior use, instead a white cement was advised (Van der Schrier, 1938), or even to leave the concrete (made with white cement) exposed. Increasingly, it was advised to avoid rendering of concrete of exterior elements in general, as the render could detach too easily and cause higher maintenance costs (Scharroo, 1940, 1951; Van der Schrier, 1938; Wattjes, 1931). Other complaints were the regular re-painting of renders when they were not made with a decorative plaster (Wattjes, 1931).

Before rendering, the concrete surface either had to be cleaned with wire brushes (Minister van Oorlog, 1906), or in case the surface was too smooth, it had to be roughened up first (Figure 7.22, see also Van der Kloes, 1893; Van der Schrier, 1938). The thickness of the render was advised to be between 10-12 mm (Van der Kloes, 1893), or 3-10 mm (Minister van Oorlog, 1906), limiting thereby the aggregate size; latter could be applied with a brush.

At the beginning of the 20th century, concrete structures were sometimes rendered with a so-called *kunstzandsteenpleister* (“artificial sandstone render”, see Figures 7.23 to 7.26). Hereby, ground natural stone was added to the mortar to imitate the colour of natural stone, and the hardened render tooled (Bergsma & Homan van der Heide, 1910b; Verhey, 1912). Its use in the Netherlands was seldom at the beginning of the 20th century (Verhey, 1912). It was sometimes disliked and

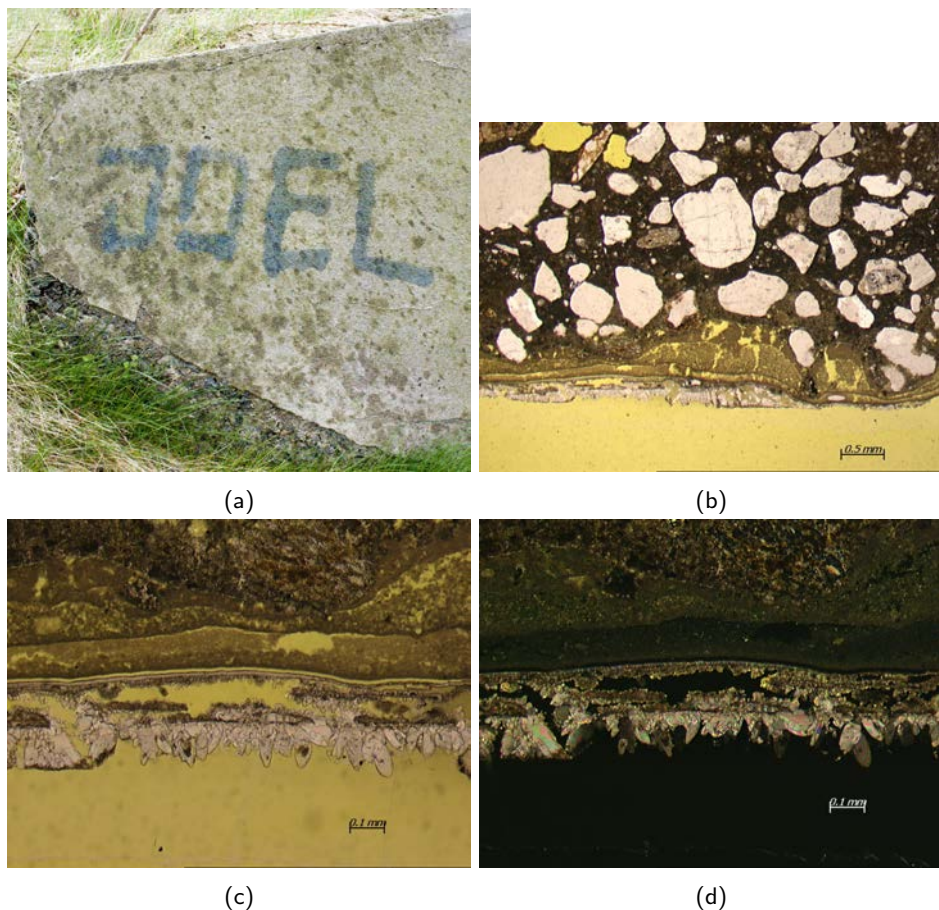


Figure 7.21 Example of a rendered plain concrete wall of a military building and the possibility to identify the layers of render with microscopy (Fort Bezuiden Spaarndam, part of the Defense Line of Amsterdam, 1897-1901, situation 2008) (a) Photograph of the end of an earth-retaining wall made from plain concrete with porphyry as coarse aggregate, visible where no plaster had been applied. (b-d) Photomicrograph (T.G. Nijland) of a thin section showing different layers applied on the concrete: a levelling layer followed by three layers of a lime based mortars and lime deposits from an unknown source at the surface. b) 25x, plain polarised light. c) 100x, plain polarised light. d) 100x, cross polarised light.



Figure 7.22 Soffit and head of a mushroom column, currently painted, with local detachment of paint. Several, irregularly spread holes in the concrete surface, applied to increase the roughness, indicate that the soffit and column were previously plastered (Van Nelle factory, J.A. Brinkman and L.C. van der Vlugt, 1926-1931, situation 2008).

viewed as a cheap surrogate for natural stone to illude the observer to see a large piece natural stone; in combination with imitation joints, the illusion increased (Rutgers, 1909). In other cases, it was considered as a good solution to improve the appearance of concrete buildings and an alternative for facing concrete (see Section 7.6). Two early examples for the application of a decorative and tooled plaster can be found in Rotterdam: the plinth of the warehouse St. Jobs (see Figures 7.7 and 7.23) and the Hofplein railway viaduct (Figures 7.25 and 7.26).

Decorative plasters using ground natural stone, such as a sandy limestone, were later sold under brand names such as *Terranova* and more commonly used in the 1930s. Other natural stones, namely Carrera marble and Euville limestone, were used as well and sold as Simili Carrara resp. Simili Euville (Anon., 1933). Such plasters could be washed out, exposing the aggregates (Scharroo, 1942b; Van der Schrier, 1953, 1960, 1968).

A different technique to modify the appearance and colour of a plaster on concrete was by applying *beton-emaille*; despite its name, this was neither a heat treatment nor a chemical reaction of the concrete, but a special plaster type applied on concrete walls. It was commonly used for interior surfaces exposed to wear and moisture, such as bathrooms and stairwells. Several proprietary systems of *beton-emaille* existed, and were made with cement (in this case, white cement) or were gypsum based, and contained metal oxides. A treatment with *beton-emaille* improved both the appearance and the resistance to environment or chemicals exposure (Klaassen, 1954; Scharroo, 1940, 1942a).



(a)

(b)

Figure 7.23 Reinforced concrete rendered with a tooled *kunstzandsteen* (former warehouse St. Jobsveem, Rotterdam, J.J. Kanters, 1912, situation 2010). a) Overview plastered wall and cantilevered balcony slabs; local colour differences are visible between original plaster and a repair from 2006. b) At a damaged area two layers of render can be seen, a bottom grey render, probably made with Portland cement and a top coloured and tooled layer.



(c)

(d)

Figure 7.24 Façade of a reinforced concrete building, combined use of artificial stone and *kunstzandsteenpleister* (artificial sandstone render, former hotel-restaurant "De Twee Steden", The Hague, Joh. Mutters Jr, 1904-1906, situation 2010). a) Overview. b) Detail of the surface with local repairs which neither match in colour nor texture.



(a)



(b)



(c)

Figure 7.25 Example of an early reinforced concrete building with a tooled *kunstzandsteen* render: the colour changes between the two renders can be explained by a severe fire during the Second World War in the yard (Van Zutphen, 1958), turning the plaster reddish (Hofplein railway viaduct, Rotterdam, A. C. C. G. van Hemert, 1900-1908, situation 2010). a) One of the last remaining unpainted segments, showing the original yellow sandstone like colour. b) Picture of the yard with a reddish plaster under layers of peeling paint. c) Picture of the yard with the same reddish plaster applied on brick works.



Figure 7.26 Stereo micrographic pictures from two differently coloured render samples of the emplacement of the Hofplein railway viaduct, both made with a greyish bottom layer (Portland cement based) and a coloured finishing layer with broken sandstone as aggregate (Pictures Laura Bolondi). a) Finishing layer is yellow-beige, the original colour (9 times magnification). b) The finishing layer is reddish due to colour changes of the sandstone aggregate caused during the fire in 1940.

7.3.2 Painting

Painting of concrete surfaces was technically not easy until the development of special cement paints in the 1930s (see for example Gray & Childe, 1943, Klaassen, 1954). Sometimes it was stated that painting of concrete was not possible at all (A.A., 1923). The problem was that traditional oil-based paints, such as linseed oil paints, could not be used without any pre-treatment of the surface. The high alkali content of fresh concrete, together with hydrated lime and in presence of humidity, reacted with the fats in the paint, causing saponification. Advices were to wait at least six months before applying an oil-based paint as the ageing of the concrete reduced the alkalinity (Roelofsen, 1940). Other options were to reduce the alkalinity of the fresh concrete by pre-treating the surface with Kesslersche fluates, such as the *bouw-fluaten*.

Kesslersche fluates, a fluosilicate, were already used for stone consolidation from the end of the 19th century, yet they were expensive. At the beginning of the 20th century, *Fluoziment*, a specially developed fluate which allowed a direct painting of a fresh cement plaster was developed (Fröde, 1910). The use of Kesslersche fluates is described in Dutch textbooks of German origin (Bergsma & Homan van der Heide, 1910a). The treatment of concrete surfaces with fluates, or fluosilicates, was advised to increase the resistance of the concrete against chemical attack (Roelofsen, 1940).

A more traditional method was to lime wash the surface (in Dutch *witten*), with the option to add pigments. A variation was to use Portland cement instead of lime, known as *grijzen* (“to make grey”), which was a mix of two parts Portland cement with five parts of water, optionally with some lime solution (*kalkmelk*) or

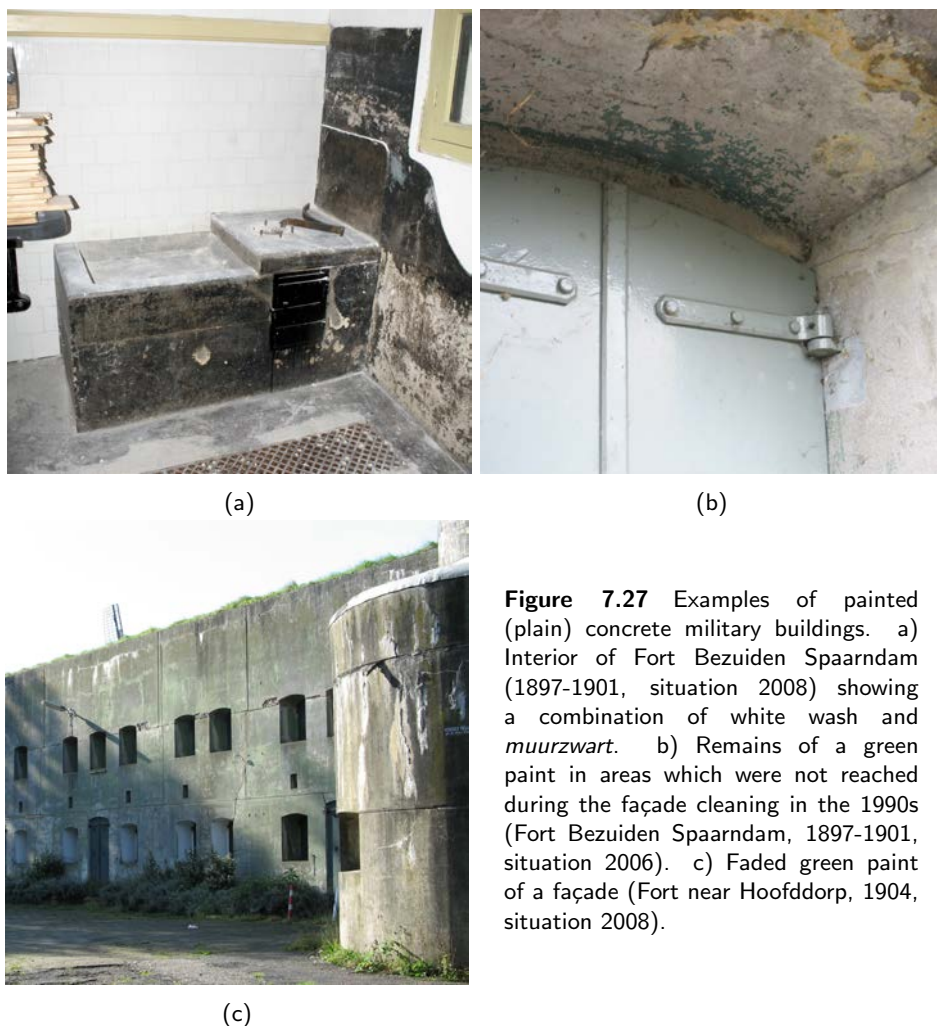


Figure 7.27 Examples of painted (plain) concrete military buildings. a) Interior of Fort Bezuiden Spaarndam (1897-1901, situation 2008) showing a combination of white wash and *muurzwart*. b) Remains of a green paint in areas which were not reached during the façade cleaning in the 1990s (Fort Bezuiden Spaarndam, 1897-1901, situation 2006). c) Faded green paint of a façade (Fort near Hoofddorp, 1904, situation 2008).

*muurzwart*² (“wall black”) (Minister van Oorlog, 1906, §235). Some examples for early painted concrete buildings, in combination with a thin layer of Portland cement render, can be found in the Stelling van Amsterdam. In the interior, white washes and *muurzwart* were applied; for the exterior a green, camouflage like, paint was applied, and depending on the degree of façade cleaning and weathering, remains can still be found (see Figure 7.27).

² *Muurzwart* was a very cheap black pigment made from carbon, as it was a waste product of the coke production (Scharroo, 1942a; Van der Kloes, 1910).

7.3.3 Tooling

Tooling is a mechanical removal of the cement film, and includes bush-hammering, point-tooling and chiselling and is one of the earliest surface finishes for concrete. The intention was to mechanically remove the undesired grey cement film of the hardened concrete, and to expose the colour and texture of the aggregates. Other initially undesired properties of the raw concrete surface were the random texture caused by the timber formwork and cement ridges caused by leaking joints. Tooling was often used in combination with coloured aggregates or coloured cement to alter the grey appearance of the concrete. The tools and patterns used were traditionally applied by stone masons.

Artificial stones were tooled from the late 19th century on to make a more vivid and varied surface (Petry, 1913). Compared with natural stone, concrete had the advantage that it was easier to tool, yet a large scale application for concrete surfaces was initially not advised for aesthetical reasons. The main visual difference to natural stone was that it was possible to achieve a hammered surface without joints, which was considered as more appropriate as it reflected the monolithic concrete structure (Von Mecenseffy, 1911). Technically, tooling of a surface required less maintenance compared to plastered concrete surfaces, which often detached (Bergsma, 1934). In the Reconstruction Period after the Second World War, more concrete specific techniques to remove the current film were applied, such as the brushing of concrete.

After the concrete had hardened sufficiently and the formwork struck, which was considered at an age of three to four weeks (Gray & Childe, 1943; Roelofsen, 1940), the surface could be tooled. The tooling of concrete was limited by the quality of the concrete, as it could not disguise all blemishes and some, such as voids, were even accentuated (Kruijf, 1912; Quimby, 1908; Von Mecenseffy, 1911). Therefore, special attention had to be given to the mixing and placing of the concrete so no irregularities or construction joints would be visible on the surface.

In the 1930s, the influence of removing the cement film on the durability of the concrete was addressed more often, as it was supposed to reduce the density of the surface. It was advised to use a watertight concrete and to increase the thickness of the concrete cover to prevent corrosion as humidity could ingress through the (micro) cracks caused by tooling (Bergsma, 1934; Wattjes, 1931). In the G.B.V. 1940, this concern is considered with the requirement to increase the thickness of the concrete cover when the cement film was to be removed (see Section 7.2).

In the first decades of the 20th century, several large scale buildings were indeed bush-hammered. The former fashion store Gerzon (Figure 7.28) is considered to be the first large scale application of exposed tooled concrete in the Netherlands (Gratama, 1915; Oosterhoff et al., 1988); other examples are the radio station Kootwijk (Figure 7.29, see also Emmen, 1923), and the industrial building HAKA (Figure 7.30). However, the original surfaces of these buildings can no longer be experienced, as they were covered during time, disguising the original colour and texture of a tooled concrete surface.



(a)



(b)



(c)

Figure 7.28 Rear façade of the former fashion store Gerzon (A. Moen, Amsterdam, 1915, situation 2011), the surface has been painted white. a) Overview of the painted rear façade. b) Detail of a pilaster of the rear façade, showing the combination of bush hammering at the column foot and point tooling above (c) Due to local damage the original colour combination of dark crushed rocks as aggregates and the grey cement can be seen; the colour of the entire façade would have varied depending on the degree of exposure of the aggregate. As the building is now painted, these effects are not visible anymore.

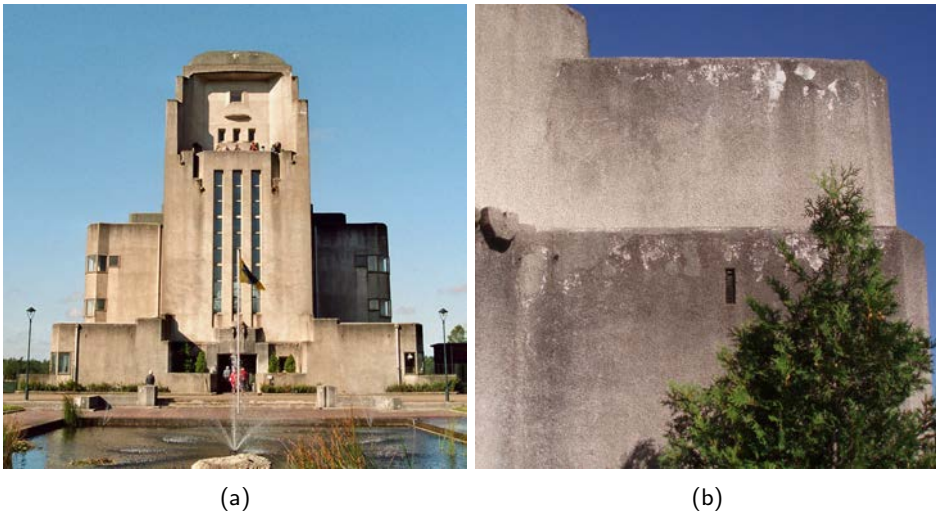


Figure 7.29 Former radio station Kootwijk: the original surface was bush hammered, exposing gravel but covered with a layer of sprayed concrete in the 1960s, disguising the original texture and colour (J. M. Luthmann, J. Emmen, 1921-22, situation 2006). a) Overview main façade. b) Detail main façade showing a soiled layer of sprayed concrete.

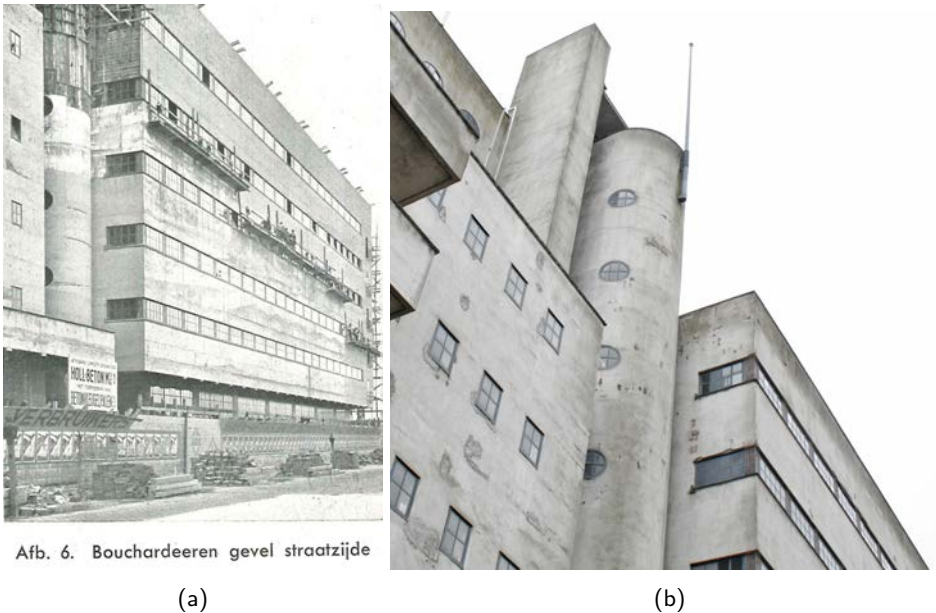


Figure 7.30 Former industrial building HAKA; the original concrete surface was bush hammered (Rotterdam, H. F. Mertens, J. Koeman, 1931 - 1932). a) Picture taken during the bush hammering of the façade (Wattjes, 1934). b) Situation 2009: the original surface has been painted white and the concrete has locally spalled.

The patterns created by tooling varied during time, and was influenced by the geometry of the concrete element (Figures 7.28 to 7.35). Large areas were often either bush hammered or point tooled (Figure 7.8, Figures 7.28 to 7.30), whereas smaller areas were chiselled. A traditional pattern was to combine bush hammering with chiselled margins (Figure 7.31, see also Von Mecenseffy, 1922); a more recent pattern, dating from the late 19th century, of polygonal forms with changing directions, is the so-called *kathedraalslag* (see Figures 7.32 to 7.33).

Caution had to be given to corners as they could easily be damaged, and therefore finer techniques were chosen or the edges were left untreated (Gilchrist Wilson, 1964). As tools, bush hammers, hand picks, or pneumatic hammers were used, latter already known at the beginning of the 20th century in Europe (Von Mecenseffy, 1911, 1922). The effects of the different tools vary, a hand pick causes large scaling; bush hammers leave a finer texture. Bush hammering was advised to be used when the concrete had already hardened and the surface could not be brushed anymore (Onderdonk, 1928).

In the 1920s and 1930s, prefabricated concrete elements such as window sills were commonly tooled, imitating natural stone (Figure 7.35). In the course of time, the tooling of concrete freed itself from the reputation of being a technique used to surrogate natural stone, and tooling was seen as an honest and logical method to show that concrete is a composite material (see for example Gray & Childe, 1943). In the reconstruction period after the Second World War, tooling was often used in combination with decorative concrete (see Section 7.7). Another area of application was tooling of decorative renders applied on concrete surfaces (see Section 7.3.1). Tooling of surfaces became out of fashion as it was too laborious, too costly and associated with health risks (Redactie Cement, 1983).

The tooling of the surface alters, besides the surface texture, the colour of the concrete, as the aggregates are exposed and fractured. Therefore, not only the tool and the way of hammering (e.g. manual or pneumatic) but also the components of the concrete and their size and distribution influence the appearance of the tooled surface. For techniques such as bush hammering the colour and type of aggregate is more noticeable than the marks of the tool. The desired fineness of the marks could influence the choice of aggregate, with fine chiselling requiring a softer aggregate (Gilchrist Wilson, 1964). Following aggregates were advised for tooled concrete surfaces: granite, porphyry, diabase and blue Belgian limestone (petit granit) debris (Bergsma, 1934). Concerning the durability of the concrete, it was advised to use aggregates which would not shatter under the blow of the bush hammer, as otherwise the bond between the matrix and the aggregate would fail, causing damage during freeze-thaw attacks (Gilchrist Wilson, 1964).



Figure 7.31 Example of a bush hammered surface with chiselled margins; the concrete is made with diabase as aggregate (housing, 1930s, exact date and architect unknown, Rotterdam).

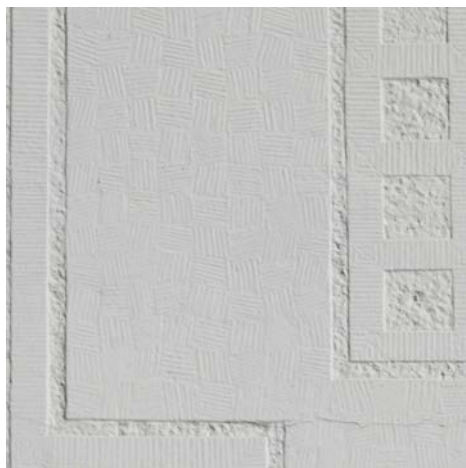


Figure 7.32 Example of *kathedraalslag* pattern, in combination with chiselled margins and point tooling on a reinforced concrete structure. Layer of white paint reduced the textural and colour details (Hofplein railway viaduct, Rotterdam, A. C. C. G. van Hemert, 1900-1908, situation 2010).



Figure 7.33 Concrete sculpture at the entrance of the Zoo Blijdorp, surface chiselled with *kathedraalslag* (Rotterdam, L. Boole; 1939-1941, situation 2011).



Figure 7.34 Example of horizontal, vertical and diagonal tooling with chiselled margins of prefabricated concrete elements (*Paleis van Justitie*, Arnhem, F. Sevenhuysen Jr., 1953-1963, situation 2010).



Figure 7.35 Prefabricated coloured concrete window sill; the texture has already partially eroded (housing, Rotterdam, exacts date and architect unknown, 1930s, situation 2010).

7.3.4 Sand blasting and washing out

A more concrete specific surface finish is to expose the coarse aggregates by either sand blasting or by washing out; that is to remove the outermost cement paste after its hardening, with or without using retarders. In terms of effect, washed out concrete is comparable to sand blasted concrete, yet technical differences exist. The effect is that the coarse aggregates become very prominent in the appearance of the concrete. By variations in the depth of the removal of the cement paste, shadow effects can be created. It will be evident that, when exposing the aggregate, the mix design becomes important, including the type of aggregate, its size, colour, and distribution, as they have strong influence on the appearance of the concrete. For example, for aesthetical reasons it was advised to use gap-graded aggregates (see Section 4.4) for washed-out concrete (Gilchrist Wilson, 1964).

Sand blasting is a mechanical method to remove the cement film and to expose the aggregates. This technique was already known at the beginning of the 20th century in the Netherlands, yet considered too expensive for a practical use (Boon, 1913). Its advantage was that it was “*practical for treating large buildings and are valuable for hardened concrete; they can remove the cement-film from quite thin facing layers which might be damaged by a hand-pick.*” (Onderdonk, 1928, p. 59). It was considered as an alternative for tooling and had similar side-effects such as affecting the watertightness of the concrete (Van der Schrier, 1938, 1942, 1957, 1968).

Compared to tooling, the concrete had to be greener³ for a sufficiently deep removal of the cement paste. After 3-4 days hardening, sand blasting would cause small holes, whereas later the surface texture would only be roughened (Von Szadkowski, 1969). However, health and environmental risks associated with sand blasting forbid its application in more recent times (Redactie Cement, 1983).

An early Dutch example of a sand blasted concrete surface is the office building *De Nederlanden van 1845* by Berlage (Figure 7.36); the quality of the sand blasted surface was considered very good as even after sandblasting no voids or construction joints were visible (Sangster, 1927; Wattjes, 1927). However, the original surface is not visible anymore as it has been plastered with visible small aggregates (Figure 7.36). An indication of the original surface finish can be found in another building by the same architect dating from the same period, the *Berlage kiosk* (Figure 7.37).

After the Second World War, sand blasting was more commonly used. For example, Schelling preferred sand blasting over hammering as it destroyed the surface to a lesser extent. Another advantage was the textural variations which could be obtained by using different degrees of sand blasting. Textural effects could be achieved by combining blasted surface areas with untreated margins to emphasise the corners (Figures 7.38 to 7.40). This was technically achieved by protecting the corners during the blasting with metal profiles (Schelling, 1950b, 1952b, 1953, 1954).

A different, more concrete specific technique to remove the cement paste without fracturing the aggregates is to wash it out, either with water or acids (Figure 7.41). The washing out of cement paste has occasionally been applied in the late 19th century; for example, the German company *Portland-Zementwerke Heidelberg-Mannheim* made exhibition objects for the Chicago World exhibition of 1893, using acid to remove the cement film (Petry, 1913). Early references of washing out concrete address its use in America, where it was applied since the beginning of the 20th century (Kruffy, 1912; Quimby, 1908; Von Mecnseff, 1911). It was later seen as the “*simplest and cheapest exposed aggregate finish*” (Gilchrist Wilson, 1964, p. 72). Variations in the depth of the removal of the concrete could be achieved. Initially, a deep removal was aesthetically recommended (Quimby, 1908). In the 1960s, it became a typical technique used for exposed concrete (Figure 7.42).

The principle of washing out concrete is to remove the cement paste with wire brushes from the concrete before it has hardened, optionally using water. As less force is applied for the removal of the cement film than by tooling or sand blasting, it is necessary that the cement paste is still weak. This requires removal of the formwork at an early age of the concrete. The advices for the age of concrete to be able to wash out the cement film ranged from 24 hours (Onderdonk, 1928), 48 hours (Gray & Childe, 1943) or even only 16-18 hours (Gilchrist Wilson, 1964). As such an early removal of the formwork contradicted the minimum time required in codes of practice, the technique was limited to non-structural elements if no

³Green concrete is the technical term for a concrete which has set but not fully hardened.

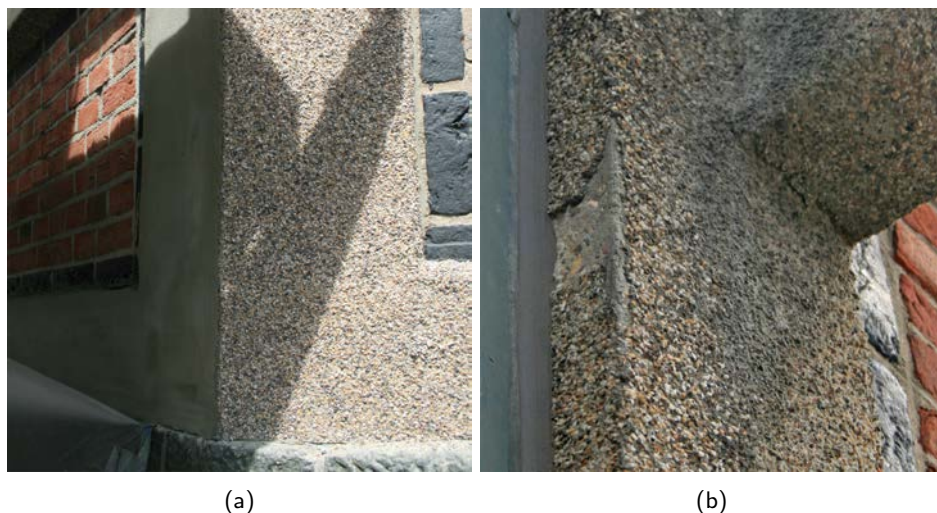


Figure 7.36 Details of the surface of the office building *De Nederlanden van 1845*, showing a render with a layer of small aggregates, instead of the original designed sand blasted surface, (The Hague, H.P. Berlage; 1921-27, extension 1954 by W. M. Dudok, partial reconstruction 1945-47, situation 2009, see also Figure 7.10a). a) Picture taken during repair in 2009, showing the application of a two layered render with small aggregates. b) Local detachment of previous render.

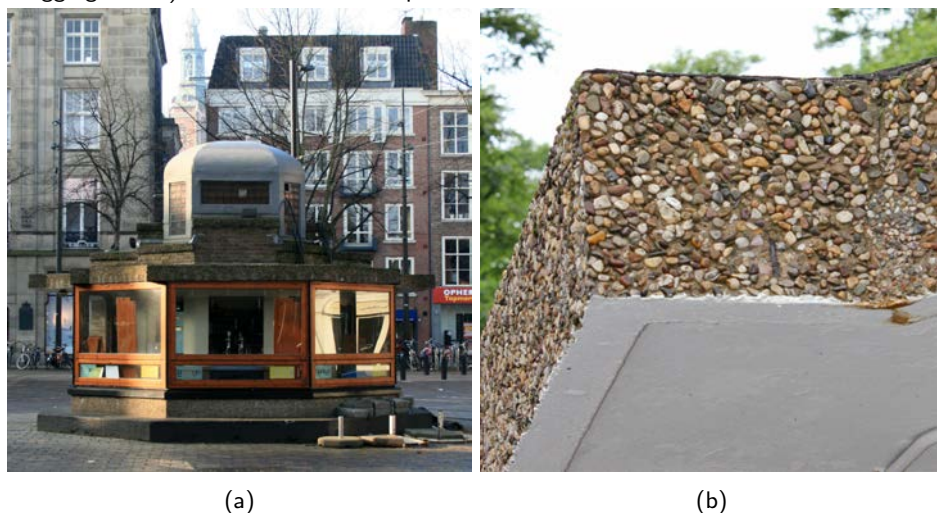


Figure 7.37 Early example of exposed aggregates, unique is that most of the exposed concrete has not been painted ("*Berlage Kiosk*", The Hague, H. P. Berlage and J. G. Wattjes, 1925, situation 2011). a) Overview showing the roof and plinth which have not been painted. b) Detail of the roof showing exposed gravel; notice the homogenous distribution of aggregate size and local repairs in the corner with smaller aggregates.

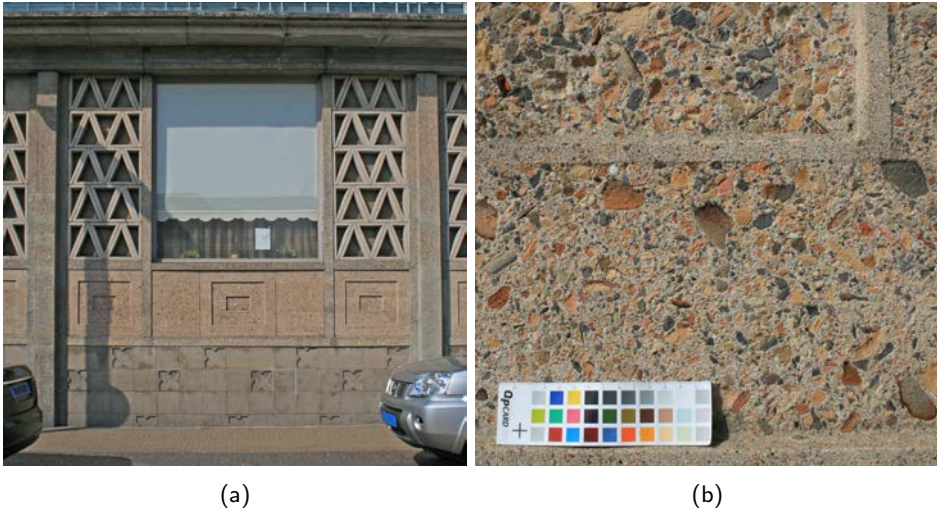


Figure 7.38 Example of the effects of combining different textured concrete, and colour effects of sandblasting (Railway station Enschede, H.G.J. Schelling, 1950, situation 2009). a) Overview showing the use of different prefabricated concrete elements: white triangular claustra elements, grey tiles, grey columns, and red panels. b) Detail of the panels, at the top the surface has been blasted more than the bottom part, exposing more aggregates. The corners have been protected and were not blasted. The aggregates used are broken glazed stoneware pipes.

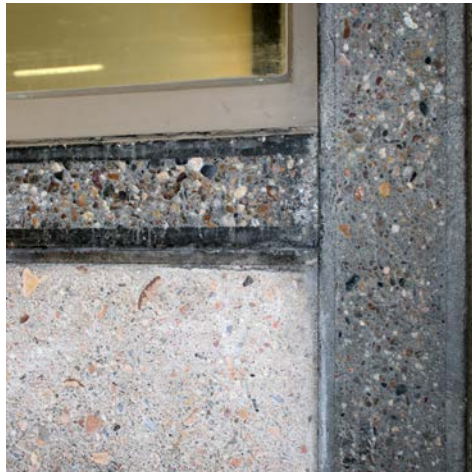


Figure 7.39 Column and window sill with sand blasted surface, edges were protected during blasting with metal. The concrete of the window sill was coloured with black carbon pigments (Railway station Enschede, H.G.J. Schelling, 1950, situation 2009).

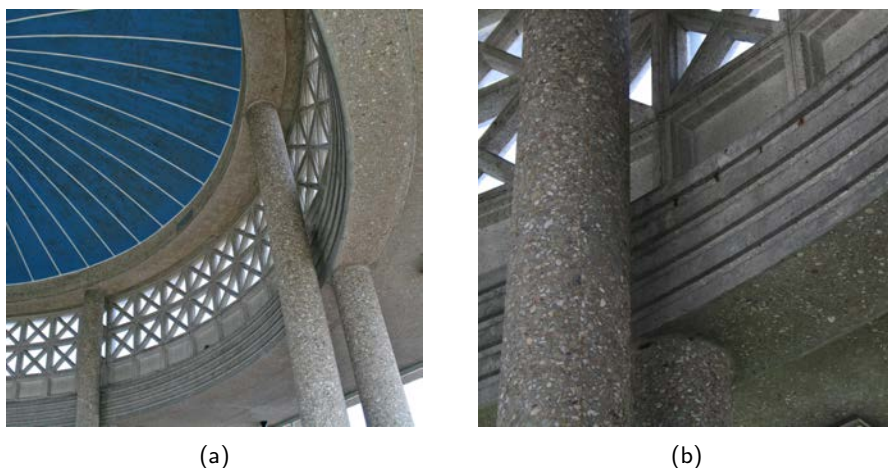


Figure 7.40 Combination of sand blasted concrete columns and soffit with smooth surfaces at the sides of the elements (Railway station Arnhem, side entrance Sonsbeekzijde, H.G.J. Schelling, 1954, situation 2009; the object has recently been relocated). a) Overview of the interior. b) Detail columns and soffit.

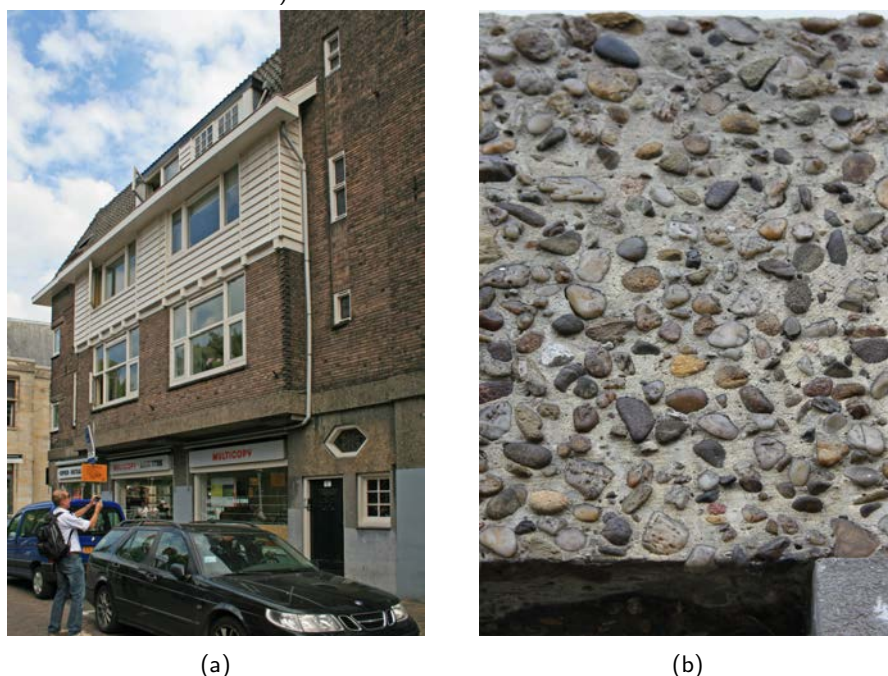


Figure 7.41 Example of early application of exposed in-situ concrete in combination with bricks for housing/commercial building (Utrecht, corner Drift/Nobelstraat, 1920s, exact date and architect unknown, situation 2008). a) Overview. b) Detail above entrance door; irregular brush strokes on the cement paste can indicate that the concrete was washed out. Unusual is the whitish colour of the cement, the shrinkage and cracking of the cement paste and the high ratio of visible cement paste.

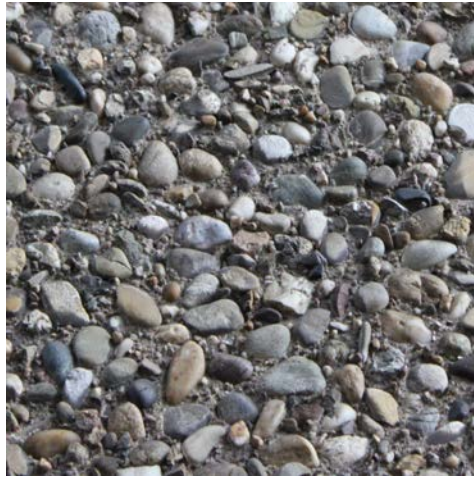


Figure 7.42 Example of washed out prefabricated concrete element (Central station, The Hague, K. van der Gaast and J. Bak, 1968-1970, situation 2011).

complementary measures were applied. For example, the minimum time before striking of the formwork was at least 4 weeks according to the G.B.V. 1912. In the G.B.V. 1930, this was reduced to 3 weeks; in case tests proved a minimum strength of 12.5 N/mm^2 (125 kg/cm^2) earlier removal was possible.

In cases when the formwork could not be removed at young age, the hardened cement paste was removed with acid (Quimby, 1908). Common acids were muriatic acid (diluted hydrochloric acid) and sulphuric acid (CUR report 36, 1966; Gray & Childe, 1943; Onderdonk, 1928). A thorough removal of the acid with water afterwards should prevent any negative effects on the durability. However, the possibility of a chloride contamination should be considered when inspecting historic concrete buildings with such surfaces. Cases in which the use of acids should be avoided were concrete with little concrete cover, limestone as aggregate and low-weight concrete (Gray & Childe, 1943).

With the introduction of retarders, the washing out of bearing concrete elements became easier. The use of retarders is mentioned from the 1930s on (Van der Schrier, 1938, 1942, 1953, 1960). They were applied on the formwork and prevented the hardening of the outer 3-10 mm of the concrete for a few days, allowing an easier removal of the cement film and fine aggregates after striking the formwork. Retarders were proprietary products and were “*mostly composed of vegetable substances in spirit and apart from retarding the set of the cement in contact with them have no ill effect upon the main body of the concrete*” (Gilchrist Wilson, 1964, p. 73).

When combining sand blasting or washing out with coloured cement (Section 7.5), it was advised to change the distribution and size of the aggregates to achieve a stronger contrast between the aggregates and the coloured cement.

It was suggested to have a discontinuous aggregate distribution without the 3-7 mm fraction. Additionally, more retarder could be used to be able to remove a deeper layer of the cement film, to thereby create better shadow and light contrast between aggregates and coloured cement (Von Szadkowski, 1969).

A different technique to remove the cement film was to brush it off before hardening. Therefore, the application is limited to horizontal surfaces. An exception are prefabricated concrete elements which could be placed horizontal for production and later used in a different position.

7.3.5 Polishing and rubbing down

Inspired by the techniques used for making terrazzo, historic concrete surfaces were occasionally rubbed down or polished (Gray & Childe, 1943; van den Berg, 1961). As it was a labour intensive treatment, it was rather expensive, and therefore limiting its practical application (Von Mecenseffy, 1911). Early example of polishing concrete on-site can be found in Germany (e.g. railway station Karlsruhe, Garnisonskirche Ulm, Petry, 1913; Von Mecenseffy, 1911). The polishing of concrete surfaces is not often mentioned in early Dutch concrete textbooks, and if so, only as a technique for the for concrete floors (for example Boon, 1908, 1931). By rubbing down the concrete surface, using special stones, the surface becomes very smooth. As the outer cement film is removed, the coarse aggregates become visible. By polishing the surface after rubbing down the concrete surface becomes more brilliant.

After the Second World War, polishing was more commonly applied, especially for prefabricated decorative concrete elements (der Steur, Herman de Groot, Hooykaas, van Veen & Jong, 1951; van den Berg, 1961). Attempts to polish concrete on-site were made, for example, at the façade at the former *Twentsche Bank* (Figure 7.43, see also der Steur et al., 1951). Examples of prefabricated rubbed down concrete elements can be seen in the works of Schelling (Figure 7.44). For the railway station in Enschede, Schelling combined the technique with rolling coarse aggregates: first a 25 mm thick reinforced concrete layer was made with above a facing layer with white cement and broken bricks as aggregate (0 - 11 mm), on which a layer of coarse aggregate (11 - 25 mm) was spread and rolled in; after three days of hardening the surface was rubbed down (Schelling, 1950a,b, 1951).

7.3.6 Metallised concrete

A very specific Dutch surface finish is the metallisation of the concrete surface (*gemetalliseerd beton*, *metallisatie*). It was patented by the Dutch brothers L. A. Sanders and A.J. Sanders in 1917. An American patent was issued in 1921, where the technique was classified as a coating process (Sanders & Sanders, 1917, 1918, 1921). The use of metallisation in the Netherlands is limited to a short period from the late 1910s to the 1930s, a period in which the grey colour of concrete was not yet appreciated and specific concrete paints did not exist either. The

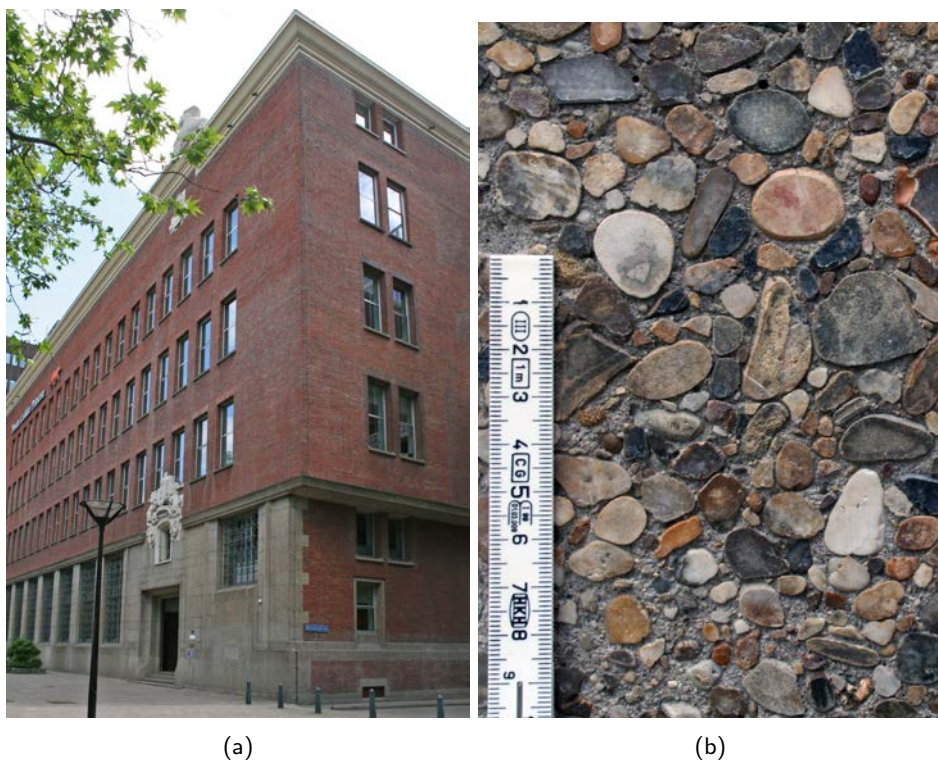


Figure 7.43 Example of a polished concrete plinth (former *Twentsche Bank*, Rotterdam, A. van der Steur; W.A.C. Herman de Groot, B. Hooykaas, B. van Veen, A de Jong, 1946, situation 2010). a) Overview façade plinth, made with individual concrete blocks. b) Detail of the polished concrete; notice that cement paste lays behind the polished surface of the aggregates, indicating its possible erosion.

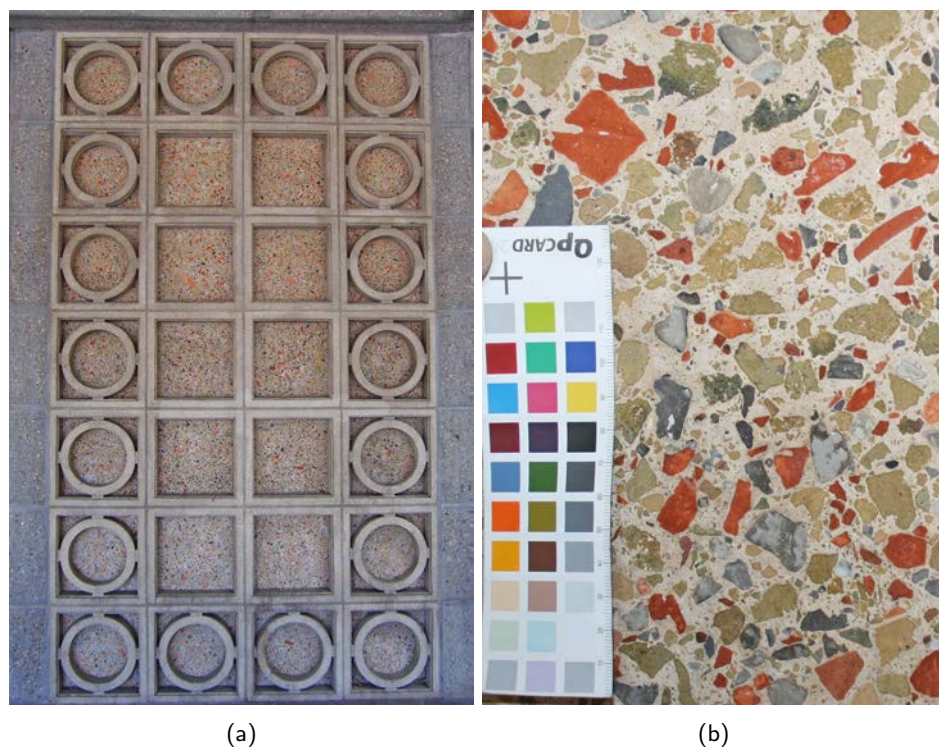


Figure 7.44 Prefabricated concrete elements filled with rubbed down concrete. As aggregates red and yellow broken bricks, and special Dutch blue coloured roof tiles (*gesmoord*), and white cement were used (Railway station Enschede, H.G.J. Schelling, 1950). a) Overview wall element (Picture T.G. Nijland, situation 2006). b) Close-up of rubbed down concrete filling, showing the variety of aggregates (situation 2009).

technique was noticed and even used abroad, for example for the façade of the former Palladium cinema in Birmingham from 1921 (A.A., 1923). The American author Onderdonk (1928) mentioned the use of metallisation in Holland since 1919. A still existing Dutch example of metallisation is a building in Amsterdam at the Rembrandt square (A.A., 1923; Oosterhoff et al., 1988). Although the concrete elements have been painted, the original surface finish can be seen where the paint is missing: a smooth surface in a dark shade of grey-green (Figure 7.45).

To alter the colour of the concrete, a solution of metal salts (sulphates, acetates, chromates, nitrates or chlorides) was applied with a brush on the hardened concrete or cement renders (Sanders & Sanders, 1918). A reaction of the salts with the cement caused a colour change. A range of 35 colours could be obtained, which could be combined to create a mottle effect (Onderdonk, 1928). The possible colours were copper green, using copper salts, cobalt blue, brown using iron salts, yellow, grey, whitish, dark shades using tin salts, shiny silver salts; the surfaces could be rough, with a granular texture, smooth, and have mat-shiny polish (Gratama, 1916; Van Loghem, 1918). For polychromatic finishes, the so-called *papiermethode* (paper method) was advised, in which a monochromic layer was applied first, which was then covered by a soaked tissue paper; the folds in the paper layer affected the speed of ingress of a second layer of metal salts, creating a random, flame like pattern (A.A., 1923). The application was quick and cheap, and after a few days, the surface could be waxed or polished (Onderdonk, 1928; Vogelensang, 1923). Waxing of the surface made the colours warmer and gave a deeper shade; such treated surfaces required no maintenance besides occasionally buffing up with a piece of woollen cloth (A.A., 1923). Metallisation did not only cause a colour change but was also supposed to waterproof the surface and increase its strength (Bouvy, 1967; Onderdonk, 1928; Sanders & Sanders, 1918).

The Dutch architect Johannes Bernardus van Loghem (1881-1940) enthusiastically embraced metallisation as the first technique that would finally ennoble concrete, freeing it from its functional appearance associated with the colour grey (Van Loghem, 1918). With metallisation, Van Loghem stated, finally a sophisticated surface finish worthy of a sophisticated material such as reinforced concrete, was available. Unlike other surface techniques, metallisation interacted with the Portland cement, showing the success of human intellect. Marvellous effects could be achieved and it seemed as if the concrete was touched with a 'magic wand' and freed from its functional limitations.

As detailed instructions about the used metal salts and the application could not be found and the technique is forgotten, it cannot be excluded that this technique was similar to other surface techniques using salts, or that it is in some variation still in use elsewhere (e.g. acid staining of concrete). A precursor of the principle to alter the colour of concrete can be seen in the Kesslersche Fluates (fluorosilicates, see Section 7.3.2), which were used, besides for consolidation, to change the colour of natural stone with iron-, chromium-, and copper-fluates (Fröde, 1910). For the colouring of concrete, the use of fluates (e.g. magnesia fluat) in the 1930s in Germany is mentioned (Springer, 2005). A rather

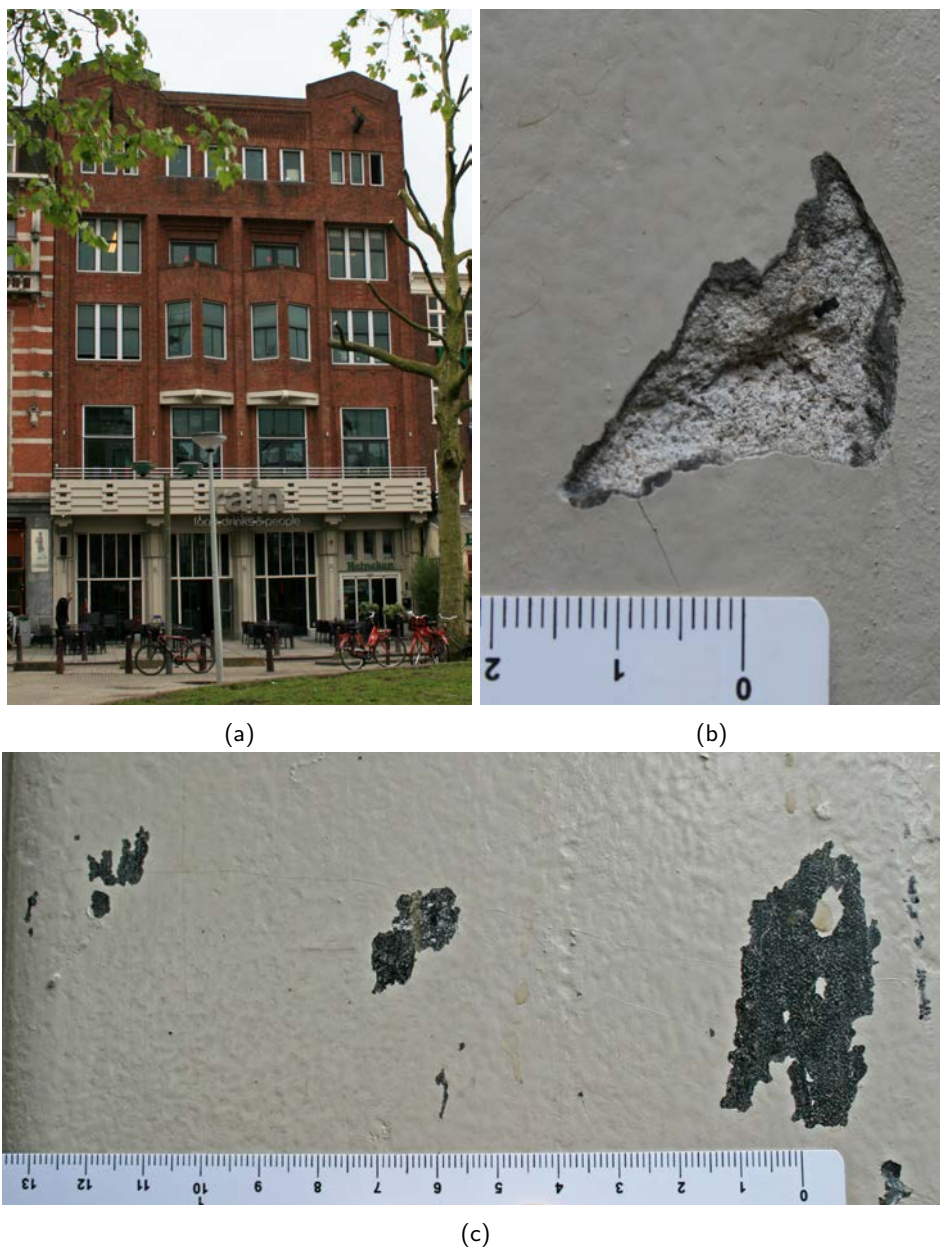


Figure 7.45 Former *Cafe la Reserve* in Amsterdam: the concrete elements (columns, balcony, cantilevered slabs) were metallised in two different colours, however they are now painted (J. van Schaik, 1918, situation 2011). a) Overview. b) Detail of a column, showing a chipped off surface; it can be seen that the colouring penetrated the surface. c) Detail of a column exposing the original surface where the paint has come off.



Figure 7.46 Advertisement of company *N.V. Algemeene Metallisatie en Betonbouw Compagnie*, offering besides metallisation of concrete and renders, also prefabricated metallised concrete elements such as chimney mantles and cement-asbestos panels (Het Vaderland, 12th April 1924).

different technique, which was often mentioned in the context of metallisation, is the spraying of a metal layer on the concrete, the Swiss *Schoop* procedure. Either melted metal or metal powder was used, and the concrete surface was required to be rough for sufficient adhesion (Scharroo, 1921; Van der Schrier, 1938, 1942).

The field of application of metallisation varied from walls, which were advised to be plastered beforehand, to smaller prefabricated elements ranging from vases to chimneys, to decorative tiles and asbestos-cement panels (brand name Eternit) (A.A., 1923). The *N. V. Nederlandsche Betonijzerbouw* had obtained the rights to carry out metallisation. After their bankruptcy, the rights were bought by *N.V. Algemeene Metallisatie en Betonbouw Compagnie* (Figure 7.46). Advertisements and reviews of metallised samples tried to show the public the possibilities of this new surface finish. Gratama, after visiting L.A. Sanders in his office and looking at samples, was convinced of this technique and wrote that the most wonderful effects similar to marble could be achieved (Gratama, 1916).

Gratama's design for a garden house made with metallised concrete is said to have been the first metallised concrete building. It was exposed during the fair in Utrecht in 1917 (Gratama, 1917); unfortunately, it does not exist anymore. The building and its surface finish were even noted and commented abroad (Onderdonk, 1928). Some other buildings and structures where metallisation was applied are known from descriptions. Two water towers designed by Hendrik Sangster (1892-1971) had metallised concrete elements: the water tower in Fijnaart had horizontal metallised, black concrete bands; the cupola and all other exposed concrete elements of water tower in Zutphen were metallised, with the cupola in a

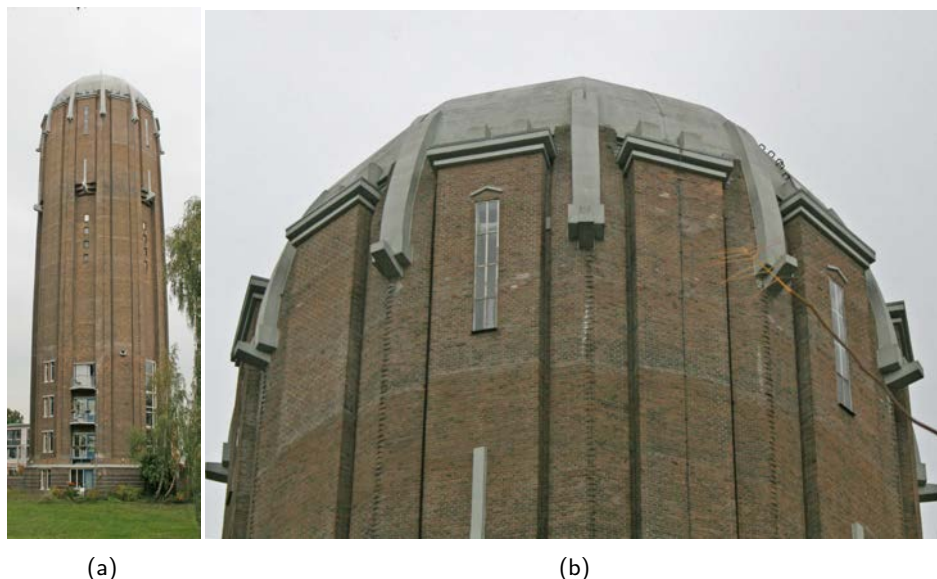


Figure 7.47 Pictures of one of the known examples where metallisation had been applied, the water tower in Zutphen (H. Sangster, 1927, situation 2009). The visible concrete elements are currently painted grey; but were originally metallised, the cupola in a yellow-brown shade, and the vertical concrete elements in brown or black. a) Overview. b) Close-up cupola.

yellow-brown shade, and some other parts in brown or black (Sangster, 1928). The water tower in Fijnaart was destroyed during the Second World War, and the water tower in Zutphen underwent some repair cycles, which caused a loss of the original surface and a change of colour (Figure 7.47). On samples taken from the water tower no traces of the metallisation could be seen anymore, a possible explanation is that the metallisation was not durable or that the concrete was of such a poor quality leading to a loss of the surface.

For the *Belgenmonument* in Amersfoort from 1917, a First World War monument of the detention centre for Belgian soldiers, the reliefs by Hildo Krop (1884-1970) were made in metallised concrete, but replaced with a French limestone in 1957 (Van der Mark, 1957). Another known example was a hotel interior in Groningen (A.A., 1923). An early intended use of metallised concrete was an unrealised bridge designed by P. Kramer in Amsterdam (Anon., 1916).

In the reviewed textbooks, metallisation is mentioned first in Scharroo's *Inleiding in de studie van gewapend beton* (1921, p. 72), where reference is made to its use as a new technique, with which decorative, coloured and durable surface finishes can be achieved. The early mentioning of metallisation in Dutch textbooks and journals can be explained by the role of Sanders in Dutch concrete technology and the resulting connections. Later, Scharroo (1946) admits that several good

results had been made with this technique but it was not often applied. It was considered to have become out of use by the 1940s (Wattjes, 1943). A revival of the technique was considered in the early Post-war years as several housing projects were to be built with concrete (Hamer, 1952). Sanders was still convinced of his technique and willing to support potential users. It was considered to be practical for prefabricated concrete elements, but could also be applied for in-situ concrete. However, several tests were considered necessary before applying metallisation on such a scale, but could not be carried out due to the lack of money. The availability of chlorinated rubber paint and plastic paints decreased the interest in metallised concrete as well (Bouvy, 1967). In textbooks, of which the first edition was published in the period of application of metallisation, or where the authors were active witnesses of the period, the technique is still mentioned in post-war editions as relicts of previous editions (Scharroo, 1944; Van der Schrier, 1938, 1942, 1953, 1957, 1960, 1968).

Looking at the durability of metallisation, it was claimed that it improved the quality of the concrete and consolidated the surface (e.g. Hamer, 1952). It was said that the treatment was long lasting, even when exposed to the elements and the colours would not fade. A repair of the surface was possible by retreating the repaired area with the same technique.

In practice, no conclusions can be drawn yet whether this proved to be correct as there are not many objects with a metallised surface remaining, and the few remaining are plastered or painted. For example, the café *La Reserve* in Amsterdam shows no sign of damage or repair, besides painting which might have also been carried out for aesthetical reasons; this might indicate that the technique has no negative effect on the durability of the concrete. Another existing building, the water tower in Zutphen did show severe damage of frost and sulphate attack. Nevertheless, if the surface treatment played a role here is not known. The sculptures of *Belgenmonument* in Amersfoort (Van der Mark, 1957) did show strong signs of deterioration which led to their reconstruction in natural stone. However, a poor construction or corrosion cannot be excluded as the main cause of damage.

7.4 Formwork finishes

An untreated concrete surface is characterised by the imprints made by the formwork. As concrete is a plastic material it mirrors the texture of the formwork it was exposed to during hardening. Initially, timber was commonly used as formwork material. The resulting surface with the irregular texture caused by the wood grains and ridges due to leaking joints between the individual boards, were disliked. Besides the previously mentioned techniques to alter the surface after striking the formwork, a different approach is to modify the formwork itself.

Surfaces with random formwork imprints were generally only acceptable when out of public sight (e.g. rear façades of industrial buildings). It was not only the texture but also the grey colour of untreated concrete surfaces which hindered the

acceptance. A large-scale acceptance depended on two main factors: the aesthetical acceptance of both the colour and texture of normal concrete, and a sophistication of concrete technology, both in mix design and execution, as mistakes could not be disguised easily. This required time and experience, and overcoming old traditions of material preference; not surprisingly, it took decades until such formwork finishes were accepted and applied on a wide scale.

In this section, the development of formwork will be discussed with regard to consciously modifying the surface texture, as well as underlying technical possibilities and aesthetical demands to understand the significance and historical context. The latter includes social-economic circumstances, as these influenced the availability of raw materials, such as timber, urging the re-use of formwork. To value the effect of the formwork on the concrete surface, it has to be understood why decisions regarding the type of formwork were made. Were they based on aspects such as the geometry and orientation of the concrete element? Or were the size and length of the available boards determining the formwork? Or were orientation and size of the formwork based on aesthetical considerations? The encountered rough, smooth or specially textured surface must be evaluated from the historical context (see also Figure 2.17 *Timeline for surface finishes applied to historic concrete*), including the technical possibilities, typology and location of the building and different scales (entire building, building part or individual concrete member), and the contemporary aesthetical concepts regarding exposed concrete.

Understanding the historical context can give first indications if an encountered formwork finish was common approach for a façade with low aesthetical requirements or a specially chosen surface finish. Comparing the surfaces in Figure 7.48, all show the irregular imprints caused by timber formwork made from individual boards. The individual boards were not levelled, causing even more surface disturbances. Although these three examples are similar in technique and resulting texture, the underlying intentions vary strongly. Figure 7.48a shows the façade of an industrial building from the late 1920s located on a site restricted from the general public. The surface texture is the result of a standard use of timber formwork boards. Figure 7.48b dates from the early 1920s; also in this case, the use of timber boards was normal; as the intention was to clad the wall with natural stone, no special attention had been given to the effects of the formwork on the surface appearance. Figure 7.48c, however, tells a different story. It is the façade of a 1960s' public building, a period where several types of formwork material existed to create either very smooth or specially textured finishes; however, in this case, an out-dated, traditional and less commonly used formwork technique was consciously chosen.

Traditionally, timber was used as formwork material, and the texture was influenced by the wood species used and the way the timber had been sawn (Gilchrist Wilson, 1964; Roelofsen, 1940). For plastered concrete, the use of a timber formwork was advised as it allowed a better bond between concrete and plaster. For exposed concrete, the surface imprints of timber form work was already early on discussed as an aesthetical problem (for example Petry, 1913; Von Mecenseffy,



(a)



(b)



(c)

Figure 7.48 Three examples of similar timber formwork finish yet with different underlying design intentions and technical possibilities. a) Façade of an industrial building, which was originally not painted (Klokgebouw, Strijp S, Eindhoven, A. de Broekert, 1928-1929, situation 2007 with a white painted surface). b) Surface of an earth retaining wall; the original intention was to clad it with natural stone, notice also the width of the formworks which is less than the other examples (unfinished Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008). c) Surface of a public building showing imprints of individual boards and nails and painted red (Faculty Building for *Elektrotechniek, Wiskunde en Informatica*, TU Delft, J.P. van Bruggen, G. Drexhage, J.J. Sterkenburg & A. Bodon, 1959-1972, situation 2006).

1911). It was not only a problem of the textural qualities but also of the unavoidable blemishes which were left mercilessly exposed. Due to the contemporary construction methods, irregularities (voids, segregation, construction joints, blowholes, colour variations, leaking joints) could not always be avoided.

Improving formwork quality was a demand for both exposed concrete and concrete in general. Early concrete textbooks often included a description of how to make concrete; besides the right mix design and how to mix concrete, they nearly always included a description of the construction and striking of the formwork. Initially, few general rules existed for the correct placement of formwork, and details could depend on the used proprietary system (Christophe, 1905; van Rossum, 1902). It was emphasised that timber should be re-used, and therefore handled carefully to avoid damage during construction (for example Scharroo, 1910a). In practice, formwork quality improved and costs reduced by a more experienced and efficient use of formwork (Boon, 1908).

It was initially advised to use timber boards only once for exposed concrete, as concrete adhered too strongly on previously used boards, which made it more expensive (Von Mecenseffy, 1911). Later on, this was overcome by using formwork releasing agents, or by sufficiently wetting the formwork before pouring concrete (CUR report 36, 1966; Roelofsen, 1940; Van der Schrier, 1938).

The factors affecting the quality of exposed concrete were discussed in more detail from the 1940s onwards. When concrete was not prefabricated, the risks of blemishes was higher. With the increased experience with making exposed concrete, the factors causing the individual blemishes were better understood and advice given of how to avoid them. For example, to avoid leaking joints, it was advised to make the joints very small (Roelofsen, 1940). Later and a more advanced advice was to seal these joints with foamed plastic strips (CUR report 36, 1966).

In some cases, the avoidance of some blemishes could cause other blemishes, and therefore priorities had to be made on which property of the surface was more important. Blowholes can be avoided, or at least reduced, when absorptive formwork materials are used such as timber; however, the absorption of the water can make the colour of the concrete less uniform. If the absorption of the formwork material is higher, the concrete tends to become darker. Even when only timber is used, the differences between the sides of the board, can influence the colour and texture of the concrete, as bark sides can make the concrete darker than when using the heart side of a board (CUR report 36, 1966).

When a uniform colour of the concrete was the main goal, it was advised to use non-absorptive formwork materials such as coated plywood, steel or plastic, and by making the formwork watertight; yet by this the risk of blowholes increases. More expensive solutions for high quality concrete with neither blowholes nor colour variations, was to apply single-use formwork materials with some absorptive capacity (CUR report 36, 1966). Another factor which influenced the colour of the concrete was the type of formwork release agents used.

Scharroo (1951) admitted that the improved formwork quality made it finally possible to produce good exposed concrete surface finishes. As a good formwork

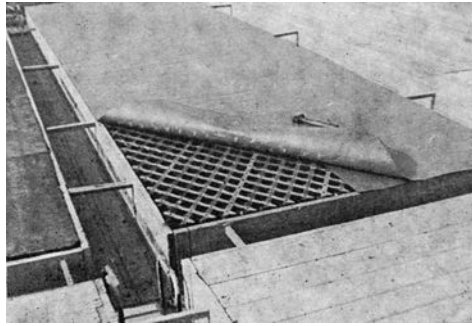


Figure 7.49 Construction of RUBORA system, showing the supportive grid and building paper (Grin & van der Veen, 1950, p. 110).

was important for the concrete quality, and as large part of the construction costs were associated to the formwork, special proprietary formwork systems, and specialised formwork companies and planners appeared (CUR report 36, 1966).

In the reconstruction period after the Second World War, with timber being scarce, re-usable and timber saving formwork systems were searched for. For slab constructions, a new Dutch system was introduced which allowed a quicker construction and reduced the labour costs: the *RUBORA* system, (short for *RUtgers BOuw-Raster*; “Rutgers building grid”, see Figure 7.49). It consisted of a wooden grid that was covered with a *Sisalkraft* paper (a water proof building paper). As the paper lining was less stiff, light imprints of the grid of the *RUBORA* systems would appear on the surface (Grin & van der Veen, 1950; Scharroo, 1950b).

Permanent formwork was applied occasionally to save timber, even before the Second World War. For the Hofbogen railway viaduct in Rotterdam, it was used for the slabs above the beams of the arches, as no access was possible to strike the formwork and thus the timber would have been lost (Braak, 1907). After the Second World War, the timber scarcity led to the use of permanent formwork, such as for the beams of the railway station Enschede (Figure 7.12) which were made from Schokbeton (Schelling, 1950b; Wigbout, 1958). Another 1950s example is the former school *Eerste Christelijke LTS Patrimonium* in Amsterdam (see Figure 7.13 and Figure 7.50), where the façade was partially made with prefabricated, sandblasted panels which were used as a permanent formwork. The interior side of the façade was made with a traditional timber formwork (Wigbout, 1958).

Steel panel formwork systems had already been discussed at the beginning of the 20th century but not commonly applied. In the reconstruction period, new steel formwork systems were introduced and considered technically better and more economic than the still generally used timber formwork, and appreciated as they created a smooth surface (Dicke, 1959; Meischke, 1954).

With increasing technological progress and options to produce different formwork finishes, the architectural application of formwork imprints was discussed. By the 1940s, two main directions can be observed: on the one hand, the aim to

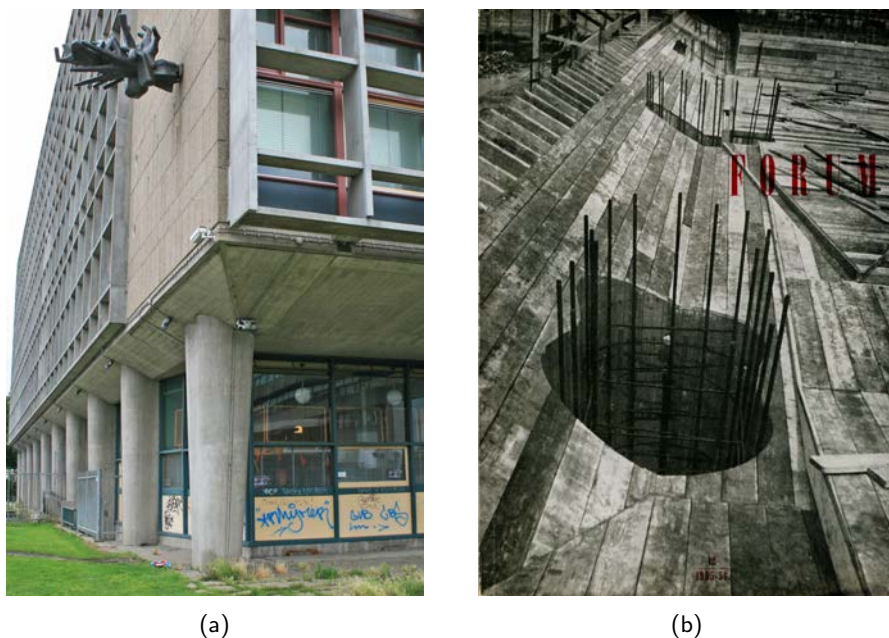


Figure 7.50 Example of the combination of permanent formwork and timber formwork for exposed concrete (former school *Eerste Christelijke LTS Patrimonium*, Amsterdam, J.B. Ingwersen and C. de Geus, 1952-1956, situation 2011). a) Corner showing soffit and columns made with timber formwork; façades made with prefabricated, sandblasted panels which were used as a permanent formwork. b) Picture taken during construction showing the timber formwork of the column and slanted slab at the corner, and the reinforcement of the column (cover, *FORUM* journal, 1955-56, 12).

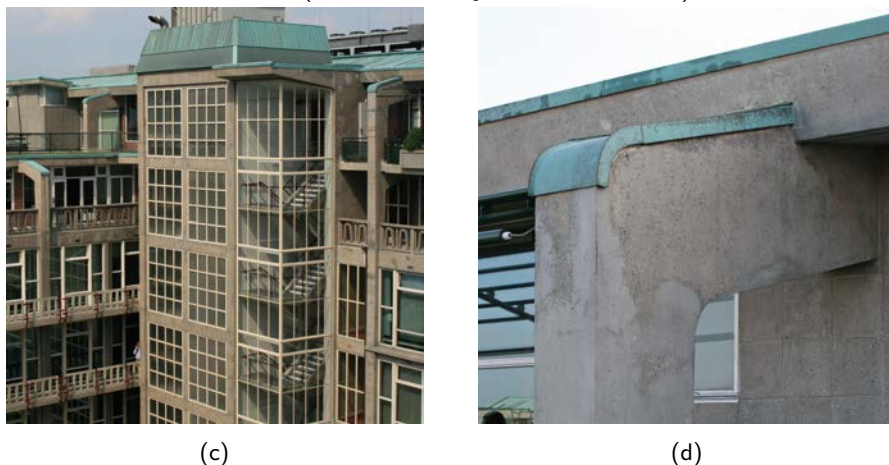


Figure 7.51 Example of smooth exposed concrete made on-site in combination with prefabricated concrete elements. During a large scale repair campaign in 2002-2005 the concrete was cleaned and previously applied paint removed (*Groothandelsgebouw*, Rotterdam, H. Maaskant, 1950, situation 2008). a) Overview inner courtyard. b) Detail columns and beam, visible are local patch repairs. The local visibility of aggregates is either due to cleaning or natural erosion.

modify the formwork to create the smoothest surface; on the other, the acceptance of wood texture as the true concrete finish (Gray & Childe, 1943).

Options to achieve a smoother surface were using smooth, planed, tongued and grooved boards, and very smooth surfaces by using plywood or metal panels (Gilchrist Wilson, 1955; Gray & Childe, 1943; Grin & van der Veen, 1950; Roelofsen, 1940; Scharroo, 1951; Wattjes, 1943). In the 1930s, a special formwork plywood covered with a layer of resin, the *betontriplex* and *betonmultiplex*, was introduced, which were still applied on traditional timber board constructions (Roelofsen, 1940; Van der Schrier, 1938, 1942, 1960; Wattjes, 1943). With the wide scale introduction of formwork systems, plywood was also applied in combination with standard panels. A 1950s example of a smooth exposed concrete surface made with plywood can be found at the *Groothandelsgebouw* in Rotterdam (Figure 7.20 and Figure 7.51, see Anon., 1951a). To create a rough surface, other options existed besides using rough timber boards, such as specially designed textural inlays (e.g. rough canvas of hessian (Gray & Childe, 1943; Roelofsen, 1940)).

When trying to identify the original texture of exposed concrete nowadays, the influence of erosion should be considered. The fine textural details of a timber formwork might have been lost and only present in zones protected from the elements or in interior rooms. On the other hand, originally smooth surfaces could have become rougher and even exposing locally aggregates.

Besides the texture, the geometric pattern created by the formwork can be modified. The geometry of the imprints caused by the formwork can be defined by the shape and size of the individual formwork elements, such as individual boards (usually timber) or larger sized panels (plywood, metal), and their orientation. The layout of the formwork can be either chosen for mainly practical reasons (re-use of timber, panel size, bearing capacity formwork) or modified for aesthetical reasons. Attention has to be given if the orientation of the individual boards is a technical solution (Figures 7.52 and 7.53) or part of the aesthetical design of the concrete surface (Figures 7.54 to 7.56). Consciously chosen geometric patterns, often in combination with different surface textures, can commonly be found on soffits from Post-War public buildings such as the Auditorium of Delft University of Technology (Figure 7.13 and 7.55) or the provincial house in Arnhem (Figure 7.56). Special geometric inlays were used as well, as for example for the plinths and frieze of the former tax office in Amsterdam by G. Friedhoff and M. Bolten (Figure 7.57). Later developments were textured rubber or thermoplastic inlays (Gilchrist Wilson, 1964).

A detail specific of exposed concrete was how to treat the joints between panels. One suggestion was to emphasise the joints by placing slats, which would create an indent along the joint (Bergsma & Homan van der Heide, 1910a; Grin & van der Veen, 1950; Scharroo, 1951; Van der Schrier, 1953, 1960). Slats were attached as well to imitate the joints of a natural stone wall (Figure 7.58). Corners required attention as well. As it was difficult and time consuming to make them sharp it was advised to chamfer them (Von Mecenseffy, 1911, 1922).

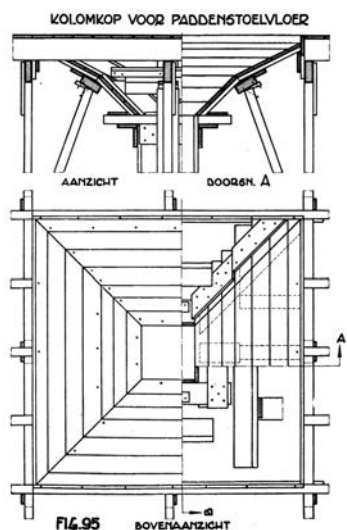


Figure 7.52 Drawings of the formwork of a mushroom floor construction column head (Grin & van der Veen, 1950, p. 53).



Figure 7.53 Geometric pattern based on the technical solution for a timber formwork of a mushroom floor (Van Nelle factory, J.A. Brinkman and L.C. van der Vlugt, 1926-1931, situation 2008, surface originally plastered, now painted).



Figure 7.54 Soffit with pattern consciously chosen by arranging individual timber boards perpendicular in squares (Train station Zutphen, H.G.J. Schelling, 1952, situation 2009).

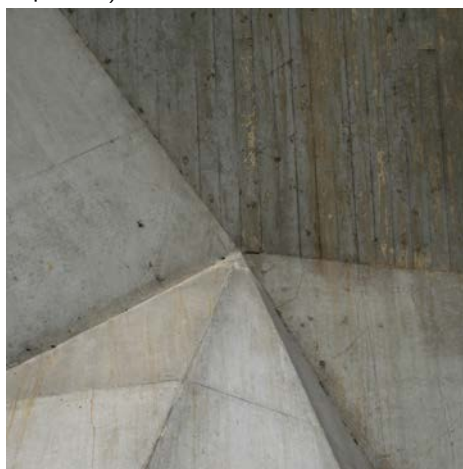


Figure 7.55 Soffit above the entrance of the Auditorium TU Delft, as formwork combination of smooth panels and timber was used (architectural firm van de Broek & Bakema, 1959-66, situation 2006).



(a)



(b)



(c)

Figure 7.56 Example of the combination of different textures, sizes and orientation of formwork imprints to create an aesthetical effect on the exposed concrete surface (Provincial house Gelderland, Arnhem, 1950-1955, J.J.M. Vegter and H. Brouwer, situation 2010). a) Overview soffit showing the combination of different textures and orientation. b) Detail of a circular indentation made with diagonal and symmetrical orientated rough timber boards, the surrounding surface was made with a smooth formwork. c) Combination of indented surface with timber formwork imprint, smooth surface and bush hammered column.

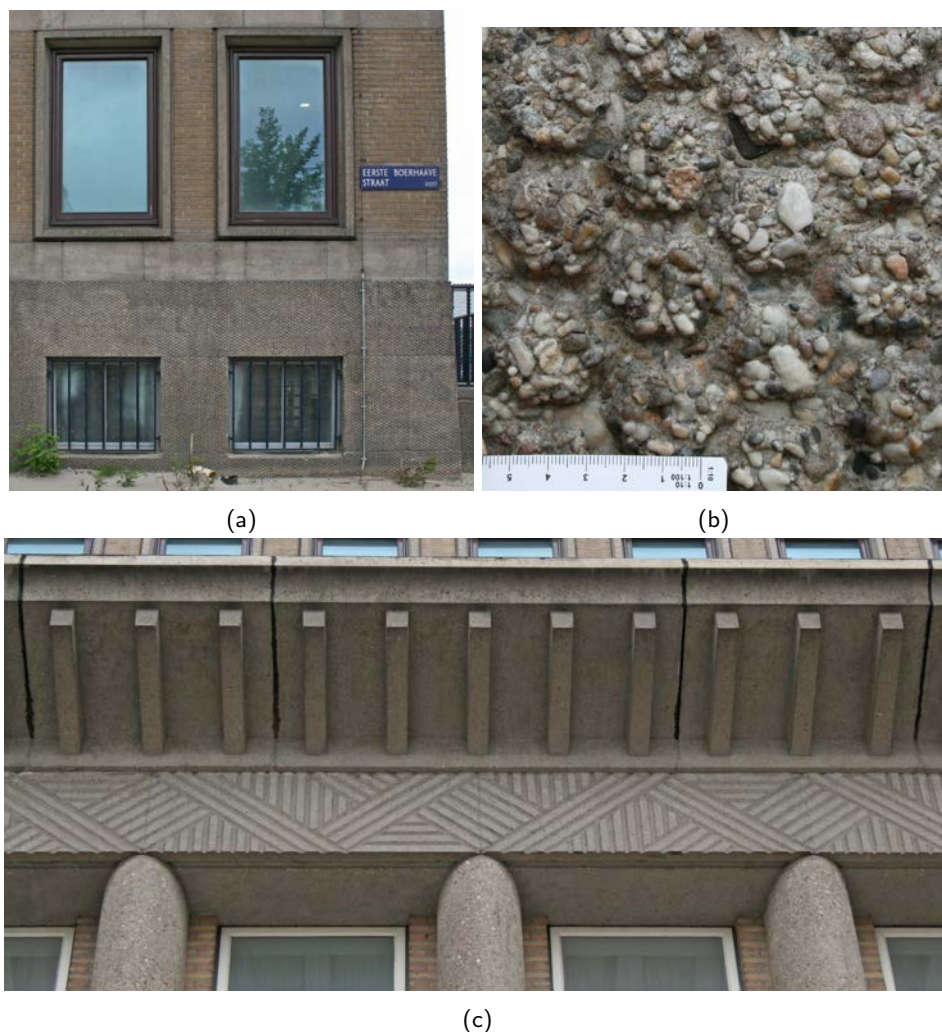


Figure 7.57 Example of the different patterns in prefabricated concrete elements made by inlays in the formwork (former tax office, Amsterdam, G. Friedhoff and M. Bolten, 1954-1958, situation 2011). a) Overview of plinth made from prefabricated concrete elements. The glossy surface appearance indicates the more recent application of an anti-graffiti coating. b) Detail of the plinth showing the pattern of hexagonally shaped indentions caused by an inlay in the formwork; the cement film was removed, exposing the gravel used as aggregate. c) Frieze made from prefabricated concrete elements where a pattern was created with inlayed elements.

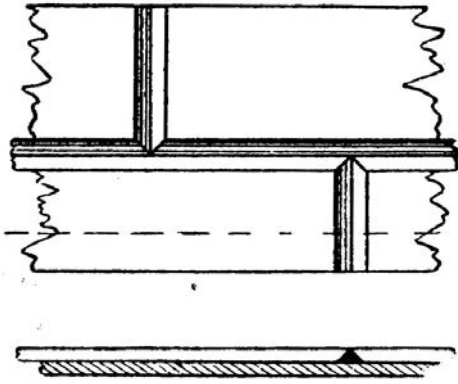


Fig. 24.

Figure 7.58 Drawing of a formwork with attached slats to imitate the joints of stonewall (Bergsma & Homan van der Heide, 1910a, p. 54).



Figure 7.59 Regularly placed openings for tie wires, later closed with a mortar, in an exposed concrete wall made with a vertical timber formwork with visible blemishes (waterways) at the joints (Faculty of Architecture, Delft University of Technology, architectural firm van den Broek & Bakema, the building burnt down, May 13 2008).



(a)



(b)

Figure 7.60 Two examples of detail rich artificial stones. a) Figures and letters cast in concrete, for the original colour see Figure 7.74 (former office building for Rotterdamsche Cementsteenfabriek van Waning & Co, Rotterdam, J. I. van Waning 1898, situation 2010). b) Sculptured artificial stone with local repairs at the bottom, where only the outlines but not the details of the texture were reconstructed (former hotel-restaurant "De Twee Steden", The Hague, Joh. Mutters Jr, 1904-1906, situation 2010).



Figure 7.61 Entrance Radio Kootwijk, relief made in-situ by using gypsum formwork. The colour difference between the entrance and the walls behind is not original, but caused by the application of sprayed concrete in the 1960s on the walls (J. M. Luthmann, J. Emmen, artist H. van den Eijnde, 1921-22, situation 2006).

As it is usually not possible to cast large concrete elements (e.g. walls) in one pour, visible joints between different pours cannot always be avoided. Without further action, these construction lines can create a wavy pattern on the surface. An option to avoid such wavy lines was to create a straight line by means of temporary placement of wooden boards on top of freshly poured concrete and, by this, control the joints' geometry, or by even accentuating them by creating a groove (CUR report 36, 1966). Another aspect which affected the surface was the holes made by tying rods. If it was not possible to strut the formwork of walls or deep beams externally, a technique which became expensive after the Second World War due to timber scarcity, it was necessary to support the formwork by placing spacers, tie-rods or wires, which however left openings in the concrete. It was therefore advised to place them in a regular pattern and to fill the holes with a mortar similar to the concrete (CUR report 36, 1966, see Figure 7.59).

Besides modifying the formwork to alter the surface of exposed concrete, special formworks were used to cast sculptures in concrete. Already with the introduction of artificial stone at the end of the 19th century, special formworks were applied, which allowed transferring detail-rich designs as seen in Figure 7.60. A known early formwork technique for such purposes was gypsum formwork, which could be produced according the design of the artist (Petry, 1913). For concrete structures cast on-site, gypsum formwork could be used in combination with normal formwork to accentuate areas on the concrete. An example of the use of gypsum formwork for on-site casted concrete can be seen in Figure 7.61 for the sculptures above the entrance of *Radio Kootwijk* (Emmen, 1923). An early example of the use of specially sculptured wooden formwork are the concrete façade elements of a shop refurbishment (Figure 7.62) by Gerrit Rietveld (1888-1964), who was originally trained as a carpenter (Kuipers, 2011).



Figure 7.62 Example of the use of a specially carved timber formwork for reliefs in concrete for the refurbishment of a shop façade (G. Rietveld, Utrecht, Oudkerkhof, 1919, situation 2011). a) Overview with the refurbished ground floor. b) Where the paint has chipped off the use of concrete can be identified. c) Detail of a column with reliefs. The surface has been tooled, and in the meanwhile painted white, easily leading to the assumption that natural stone had been used.

7.5 Constituents to colour concrete

The normal grey colour of concrete can be changed by consciously choosing special coloured constituents, such as pigments or special aggregates (e.g. ground natural stone) which are added to the concrete during the mixing process. To appreciate the specially chosen aggregates their use was often combined with surface finish techniques which would expose the aggregate (Sections 7.3.3 and 7.3.5). As coloured constituents were more expensive than constituents of normal concrete, economic solutions such as limiting the use of coloured concrete the outer facing layer of the concrete were applied (see Section 7.6). Common examples of using coloured concrete are natural stone imitation and decorative concrete.

The use of coloured concrete required good craftsmanship; therefore coloured concrete was already early on prefabricated as a better quality could be achieved. In the Interwar period, an increased application of coloured concrete, often in form of smaller prefabricated elements can be noticed. In the Post-war reconstruction period, prefabricated coloured concrete elements were used for mass housing (Figure 7.63). A reason was the lack of building materials, including brick, the traditional Dutch building material, and of skilled workers, leading the Dutch government to subsidise the use of prefabricated building systems (Nijland, Zijlstra, Castenmiller, Koelemij, Stroux & Heinemann, 2009). Besides the better quality, the lower production costs supported the prefabrication (Kraaijvanger, 1962; v.d.V., 1962).

7.5.1 Colour of the cement

The natural colour of Portland cement is grey due to its iron oxide and manganese oxide content. When trying to change the colour of the concrete, the grey colour causes technical problems as lighter colours, such as yellow, are turned into a dirty colour shade (Püttbach, 1987). Therefore, white cement was mainly used for coloured concrete (see Figure 7.64 and Section 3.6.3). It was and still is more expensive than ordinary Portland cement, as the production requires much higher burning temperatures (Neville, 2008). It is often used as a basis for coloured cement, as it is easier to colour and requires less colour pigments to achieve a good hue (CUR report 36, 1966). Besides white Portland cement, white cement based on magnesia cement have been mentioned to have been used. Nowadays, the use blast furnace slag cement, which becomes more homogenous in colour after oxidation, is more common when producing coloured concrete.

The colour range of coloured concrete was initially limited. Van der Kloes (1893) mentioned as possible colours red, yellow, blue, black and white. Slightly later references broadened the colour range to dark grey, different shades of red and green, whilst admitting that it was difficult or impossible to colour cement white due to the grey colour of Portland cement (Büsing & Schumann, 1905). With the introduction of white cement at the beginning of the 20th century, white concrete became possible as well.



(a)

(b)

Figure 7.63 Example of black and light coloured concrete elements (apartment buildings and garage, Slotterhof, Amsterdam, J.F. Berghoef 1958-1960, situation 2009). a) Overview rear side garage with a stripe pattern achieved by using differently coloured elements, and the dark coloured apartment building in the back. b) Detail of the joint between dark and light coloured elements, at a damaged area in the black elements it can be seen that the concrete is coloured through and through.



(c)

(d)

Figure 7.64 Example of the use of white cement for a prefabricated window casing. Beside white cement, hydraulic lime, chert as fine aggregate and yellow ochre (limonite) as pigment were used (Van Rhijn, 2010) (Stationspostkantoor Arnhem, H. L. Engberts 1955-1961, situation 2010). a) Overview with local spalling. b) Spalled concrete, notice the lack of coarse aggregates and the darker colour at the surface due to soiling.

A challenge when reviewing historic documents for the use of pigments to colour concrete are the variations in terminology. Traditional pigment names can be encountered in the late 19th and early 20th century, replaced by chemical terminology in the middle of the 20th century. An explanation is that the period of application for historic concrete overlapped with the transition from traditional pigment terminology and use of natural pigments, to synthetically produced pigments and a naming based on general chemical terms. For example Van der Kloes (1893) used *doodekop* (refers to caput mortuum) which is a synonym for Venetian red (Onderdonk, 1928; Parry & Coste, 1902), and is called now sometimes, using a general chemical term, red iron oxide (Buxbaum & Pfaff, 2005; CUR report 36, 1966; Roelofsen, 1950).

An overview of synonyms for different pigments and indications of the chemical composition for the state-of-the-art at the beginning of the 20th century can be found in Parry & Coste (1902). Concerning the correctness of terminology and chemical identification of pigments discussed in historic concrete textbooks, considerably inaccuracy and inconsistencies can be noticed. This might be explained by the engineering background of the authors and the influence of common practice and terminology. A detailed review of the chemistry of pigments used for historic concrete is outside of the scope of this thesis. An overview of pigments referred to in historic documents is given in Appendix E. What is clear, however, is that the advices for pigments changed, based on the increasing insight into the influence of pigments on the durability of concrete and into the pigment itself.

Besides changes in terminology, the applied pigments varied as well during time. Some colour pigments used for historic concrete are not used anymore. One reason is that experience has shown that the colours are not lightproof or that the pigments themselves might be harmful for the concrete. Another dimension, which is not reflected in the changing terminology, is the changes in production, quality (e.g. purity, particle size), chemical composition and preference.

The groups of pigments used for cement and/or lime based building materials are “*synthetic or natural oxides and hydroxides of iron; oxides of chromium, titanium and manganese; complex inorganic pigments, [...] with cobalt, aluminium, nickel and antimony oxides and hydroxides; ultramarine pigments; phthalocyanine blue and green; elemental carbon (should be regarded as an inorganic pigment); [and] blends of the above materials*” (NEN-EN 12878:2005). The classification encountered in the 20th century consists of the following groups: natural pigments, with the subgroups mineral pigments and sometimes ground natural stone, synthetic inorganic pigments, and synthetic and natural organic pigments.

Not all pigments can be used to colour concrete, as some can affect the durability and strength of the concrete. The alkalinity of the concrete can affect the colour, and some pigments are not durable under weathering or exposure to UV light; therefore durability test of pigments exist now and are standardised (NEN-EN 12878:2005). As for other aspects concerning concrete technology, also here experience had to be gained to identify suitable pigments.

A precursor of coloured concrete was the colouring of tiles. In his historic

review of concrete, Scharroo (1946) refers to a French publication by Fleuret (1807) where the use of coloured cement for the fabrication of floor tiles is described. The possible colours were black, blue grey, brown, white and yellow, and the pigments were either mineral or organic. Similar pigments were used for concrete and artificial stone in the late 19th century. Van der Kloes (1893) mentioned for artificial stone the use of ochre for yellow, caput mortuum for red, ground coke for black and lime for white.

In the 19th century, mainly mineral pigments were used to colour concrete. Mineral pigments are finely ground natural stones (e.g. malachite, azurite, or lapis lazuli), and can be very expensive. Cheaper synthetic alternatives with similar chemical compositions existed already in the 19th century (Parry & Coste, 1902). Such pigments were used for facing layers; yet, their use was advised against, as they caused a decrease in the strength, inhomogeneous colour and were strongly affected by weathering (Verhey, 1912).

In the 20th century, research into the chemistry of pigments and their synthetic production increased, resulting in a wider scope of colours and pigments, mainly inorganic pigments based on iron oxides and titanium oxides (Buxbaum & Pfaff, 2005). Inorganic pigments, and especially oxide pigments, are considered to be the most suitable to colour concrete (Püttbach, 1987). Synthetic inorganic pigments were either made from waste products from the chemical industry such as iron salts or made from chemical components (Roelofsen, 1950). They had a better hue and were therefore preferred over mineral pigments (e.g. hematite, goethite, umbers, sienna), which had a high percentage of non-colouring components (Buxbaum, 1998; Scharroo, 1942b). Synthetic inorganic pigments have a pure hue and are very effective, requiring only a little quantity for colouring (Buxbaum, 1998; Von Szadkowski, 1969). The main types of synthetic inorganic pigments used to colour historic concrete were iron oxides, titanium dioxides, cobalt oxides, and chromium oxides (CUR report 36, 1966; Ramachandran, 1995; Roelofsen, 1950). Most pigments are nowadays synthetic, besides some pigments for brown and red colours are based on iron oxides, which are available as both natural and synthetic pigments (Buxbaum & Pfaff, 2005; Ramachandran, 1995).

Not all types of inorganic pigments were recommended for concrete as they were not durable in its alkaline environment, including traditional inorganic blue pigments such as Berlin, Milori, and Prussian blue, cadmium red, chromate yellow (CUR report 36, 1966; Råde, 1968), lead and zinc white (CUR report 36, 1966; Probst, 1919), chromate and cobalt green (CUR report 36, 1966).

The use of synthetic organic pigments for concrete, for example aniline and tar based pigments was already discouraged from the first decades of the 20th century. Most organic pigments are not suitable as they are neither lightproof nor stable in the alkaline environment of concrete (Cimenteries et Briqueteries Réunies N.V. (C.B.R.), 1934; Probst, 1919; Råde, 1968; Roelofsen, 1950; Scharroo, 1942b; Von Szadkowski, 1969). An exception is carbon black (see Figure 7.39), which fulfils the requirements for a good colouring pigment, although this was sometimes doubted (for example Von Szadkowski, 1969). A more recently developed organic pigment

which can be used for concrete is phthalocyanine for blues, which is based on copper complexes (Ramachandran, 1995).

Although it was known that organic pigments did not fulfil the requirements for a good cement colour, they were sometimes added to produce cheaper and (temporarily) more intense colours. Inorganic pigments could be adulterated with aniline or with harmful inorganic components such as clay, gypsum, barium sulphate and chalk, and tests for the purity of pigments were recommended (Büsing & Schumann, 1905; Probst, 1919; Van der Kloes, 1908a). Ultramarine blue was known to be often mixed with gypsum. A high gypsum content could cause a degradation of the concrete within a few years. A contamination with gypsum of the colours red and yellow was possible, as they are made from waste products of the production of sulphuric acid and alum (Van der Kloes, 1908a). Other developments concerning the availability of pigments were related to the increasing insight into the health hazards of some pigments at the beginning of the 20th century, leading to the prohibition of using pigments containing lead, with an exception of yellow chromate of lead (van den Broeke, 1919).

In the context of the durability of concrete, the maximum pigment content was discussed, as a higher pigment content did not increase the hue but had a negative effect on the concrete (Roelofsen, 1950). The recommendations for the maximum pigment content varied during time and depended on the pigment type. A commonly recommended maximum content for (oxide) pigments was 10% of the cement weight (Bond van Fabrikanten van Betonwaren in Nederland, 1957; CUR report 36, 1966; Marsh, 1904; Onderdonk, 1928). For the organic pigment carbon black, the advices for maximum percentage varied from 1% to 3% of the cement weight (Bond van Fabrikanten van Betonwaren in Nederland, 1957; CUR report 36, 1966). In practice a pigment content of 1% relative to the cement weight (Kraaijvanger, 1962), respectively 3% (CUR report 36, 1966) was considered sufficient.

Besides the pigment content, the particle size of the pigments affects the colour and its dispersion. This is considered nowadays in the production and when mixing different pigments (Püttbach, 1987; Ramachandran, 1995). The particle size was already considered in the production process in the middle of the 20th century, and was chosen depending on the wavelength of the desired colour (for example CUR report 36, 1966). A more uniform particle size resulted in better colours and therefore supported the use of synthetic pigments; the manufacturing process allowed a more uniform particle size as it would have been possible by grinding natural pigments or pigments gained from waste products (Püttbach, 1987).

The general advice to make a well coloured concrete was to use a sound inorganic pigment or a suitable organic pigment, not use more pigments than necessary, and mix the concrete carefully (Roelofsen, 1950). The aesthetic impression of the finished concrete was not only affected by the pigments, but also by the colours of the cement and of the aggregates, the water/cement ratio, the absorption of the formwork, the curing, and the surface finish (CUR report 36, 1966; Püttbach, 1987; Von Szadkowski, 1969).

The colour of the concrete can change when ageing. Apart from an undesired fading of the pigments themselves, the brightness and intensity can be affected due to weathering and soiling. Erosion of the cement film can expose the coarse aggregates, creating a composite colour of cement and aggregate (Figure 7.65). White deposits due to efflorescence can reduce the intensity, and have a stronger visual impact on coloured concrete than on grey concrete (CUR report 36, 1966; Ramachandran, 1995).

Roelofsen (1950) mentioned following (external) threats for colour changes of concrete, which are still valid for modern concrete:

1. In the first 6 months the water content of the concrete changes, the colour becomes lighter.
2. The cement film can erode, exposing aggregates.
3. Deposit on the surface.

A concrete colour different from the normal grey cannot only be obtained by adding pigments or aggregates, but the colour can vary due to the used cement type as well. Blast furnace slag has a lighter colour, and depending on the carbon content, fly ash can make concrete darker (Neville, 2008). Iron-ore cement is dark green, high alumina cement⁴ nearly black (Probst, 1935). When lime is used as main binder the mortar is white as well, trass additions can turn the colour more brownish.

Some durability issues are not relevant for modern day concrete anymore as they seldom occur due to improved techniques. However, they can be encountered in historic concrete buildings. For example, modern coloured concrete is designed to be lightproof and the pigments are resistant to the alkalis present in the concrete. This, however, was not always the case for the pigments used for historic concrete. Organic pigments, except sometimes carbon black, are not recommended anymore. From the Post-War years on, doubts concerning organic pigments were expressed more commonly. Roelofsen (1950) did not advise the use of organic pigments as, for example, the silicate acid, part of ultramarine blue, can react with the lime, causing fading; Onderdonk (1928), however, recommended the use of ultramarine blue only a few decades earlier. Probst (1919) described the use of already then considered inferior organic pigments, which were sometimes applied as they were cheaper.

7.5.2 Coloured aggregates

The colour of concrete can be modified by the aggregates used. Fine ground natural stone was used when trying to imitate natural stone, often without coarse aggregates. Whereas such fine aggregates would be considered as filler nowadays, they were seen as a pigment at the beginning at the 20th century. They were a better and more affordable alternative than traditional pigments (Section 7.5.1) and

⁴Special high alumina cements used as repair mortars with an Al_2O_3 content of 70% are white.

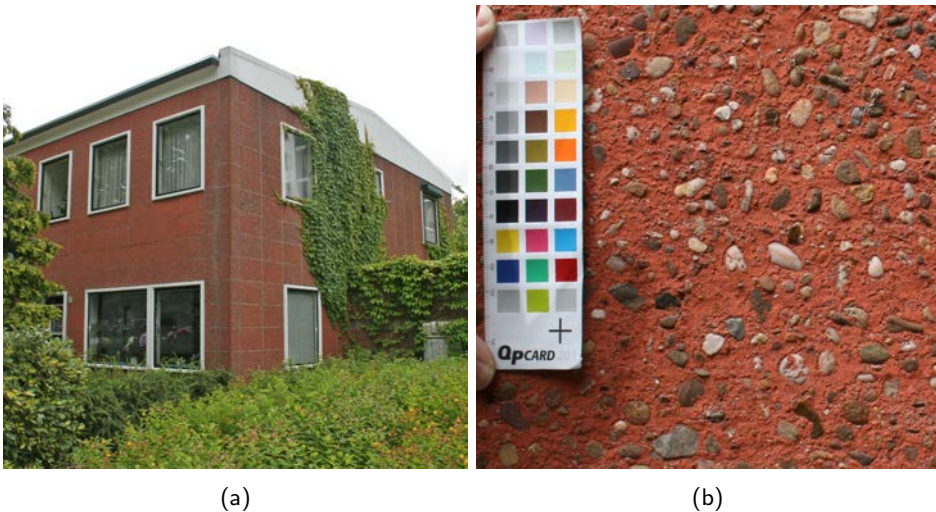


Figure 7.65 Example of red concrete elements; the current appearance is influenced by the erosion of cement film, exposing more aggregates (housing Slotterhof, Amsterdam, J.F. Berghoef 1958-1960, situation 2009). a) Overview, notice the redder colour in protected zones such as under the window sills. b) Detail surface showing the red cement paste and different coloured gravel.

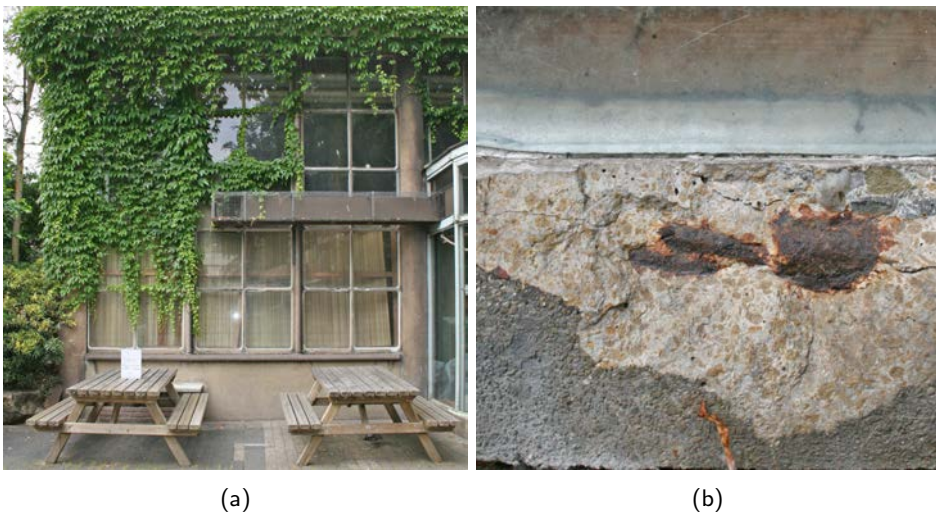


Figure 7.66 Example of beige and pink coloured prefabricated concrete elements (West wing of the “Rivièrahal” of the Zoo Blijdorp, S. van Ravesteyn, 1939-1941, situation 2011). a) Partial overview of the façade. b) Detail of reinforced concrete frame; due to soiling the use of sand stone coloured aggregate and white cement is only visible where the concrete has spalled.

considered to be the only “pigment” suitable for achieving a good coloured concrete as they are cement proof (resistant to the alkalis), lightproof and weatherproof, efficient, of intensive colour, easy to mix, and neither affected the strength of the concrete nor the time of setting (Probst, 1919). Different kinds of ground natural stone were available and could be used instead of sand as fine aggregate. Natural stones mentioned to be suitable were sandstone, limestone, marble, basalt, porphyry, granite, quartz, diabase and glimmer (mica) (Büsing & Schumann, 1905; Petry, 1913; Probst, 1919; Roelofsen, 1940; Verhey, 1912). Especially the textbook “*Die Herstellung der Zementwaren und Kunststeine*” by Probst (1919) gives detailed mixtures not only in terms of ground natural stone but also in terms of binders to achieve high quality natural stone imitations. The use of ground natural stone, together with the use of natural pigments in general, decreased during time, and did not play any major role more in the middle of the 20th century (Roelofsen, 1950). A niche market where it was still applied was for prefabricated decorative concrete (see Section 7.7).

Dutch examples for the use of natural stone to colour concrete exist, for in-situ concrete as well as for decorative renders applied on concrete (see 7.3.1). An example for the use of ground natural stone in combination with Portland cement as a plaster, *kunztandsteen*, for in-situ concrete as well as prefabricated artificial stone can be found in the former Hotel-restaurant *Twee Steden* (Figure 7.2 and 7.60) in The Hague (Gratama, 1912; Scharroo, 1916). Ground sandstone was added to the decorative plaster used for the Hofplein railway viaduct (see Section 7.3.1 and Figure 7.26). For decorative concrete, and especially for window sills, ground natural stone was used to colour the concrete.

The colour of coarse aggregates mainly influences the colour of concrete when the aggregates are exposed by removing the cement film (see Sections 7.3.3 and 7.3.5). Besides the colour of the aggregate, their texture, shape, grading and distribution influence the appearance of the concrete. A wide range of natural aggregates to colour the concrete was advised over time, including (crushed) gravel, basalt, porphyry, quartzite, granite, limestone, marble, flint stone, diabase, quartz, and ore (Bond van Fabrikanten van Betonwaren in Nederland, 1957, 1964; Bonnema & Vegter, 1946; Onderdonk, 1928; Schelling, 1950b; Van der Schrier, 1938). For these aggregates, similar restrictions as for the normal aggregates applied, such as availability, costs, size, or grading, yet the emphasis on the aesthetical properties could justify deviations (see Chapter 4 *Aggregates*).

For example, crushed rock was used for concrete structures with higher demands towards strength at the beginning of the 20th century (see Section 4.3). They were more expensive than normal gravel. Their use for exposed concrete structures indicates a conscious choice. An example of the use of porphyry in combination with a tooling of the surface can be found in the former fashion store *Gerzon* (1915) in Amsterdam by Adriaan Moen (1879-1950, Figure 7.28). Sometimes, combinations of crushed natural stone were applied, like for example at the Leiden astronomical observatory, where four different limestones were used to mimic natural stone (Nijland & Heinemann, 2008). In other cases, the higher costs

of crushed stone led to the choice of normal gravel. For Radio Kootwijk crushed stone was first considered, yet try-outs showed that the difference to concrete made with gravel when bush-hammered was not significant enough to justify the higher costs of crushed stone (Emmen, 1923) (Figure 7.29 and Figure 7.61). In the 1930s, an increase use of coloured, prefabricated concrete can be observed, using crushed natural stone to alter the colour of the concrete. An architectural ensemble of such concrete can be found the Rotterdam Zoo Blijdorp built by Sybold van Ravesteyn (1889-1983) between 1938 and 1940 (Figures 7.66, 7.3, and 7.11).

Besides crushed natural stone, several artificial materials were used: broken ceramic materials (e.g. stone ware, tiles, bricks), broken glass, metallurgical slags, broken mirror glass (Bond van Fabrikanten van Betonwaren in Nederland, 1957, 1964; Bonnema & Vegter, 1946; Schelling, 1950a,b, 1952a).

Again, the Post-War railway stations by Schelling are salient examples of exploration of the effects of special aggregates (Figures 7.67 to 7.70). Schelling carried out trials to find suitable aggregates for coloured concrete, including broken ceramic materials, glass and mirror glass (Schelling, 1950b, 1952b). Blue and yellow broken glass and mirror glass were used to create glimmering effects at the top of chimney towers (Figure 7.67); crushed bricks in yellow and red, broken blue roof tiles in combination with white cement, and an exposure of the colour by rubbing down the surface (Figure 7.44); broken stoneware was used in combination with sand blasting (Figure 7.38, Schelling, 1950b). The choice of aggregate depended on the type and the location of the element. For exterior elements in the train station Enschede, Schelling appreciated quartz and quartzite, for interior elements granite (Schelling, 1950b). Crushed flint stone with its shape and colour differences were valued as they gave the surface a vivid character (Figure 7.68, see also Schelling, 1952a, 1953). For claustra elements in the train stations Hengelo and Enschede (Figures 7.69 and 7.70), Schelling chose crushed white gravel from the Dutch town of Brunssum, which was known for its rather expensive white gravel and sand, in combination with white cement (Schelling, 1950b, 1952b, 1953).

For coloured concrete, a variety of aggregates was used; some now considered to be of poorer quality and known to cause deterioration. Their choice was not only based on technical and economic facts, but also aesthetical demands. Aggregates can make up to 70% of the concrete, and influence its strength and durability. Porphyry can cause ASR; recycled crushed bricks can be contaminated with gypsum from a possible plaster and, depending on the gypsum content, cause a delayed formation of ettringite. Additionally, some aggregates, although showing no signs of deterioration, might not meet present day standards (see Nijland & Heinemann, 2008).



(a)



(b)

Figure 7.67 Chimney towers of two railway stations by H. G. J. Schelling. The concrete was made with broken mirror glass and broken glass (around the clocks, and top part), reflecting the sun light. a) Railway station Enschede, 1950, situation 2009. b) Railway station Hengelo, 1952, situation 2009.



(a)



(b)

Figure 7.68 Façade of the railway station in Zutphen made from prefabricated, sand-blasted panels with different aggregates to achieve the horizontal colour pattern (H.G.J. Schelling, 1952, situation 2009). a) Partial overview with visible reddish and grey horizontal bands. b) Detail of the façade showing the use of crushed flint stone for the darker panels (top) and broken bricks for the red panels (bottom).

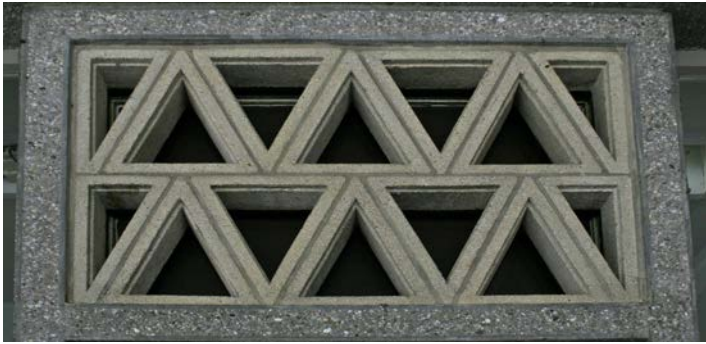


Figure 7.69 Combination of *claustra* elements made with white Brunssum gravel and white cement surrounded by elements made with normal, although whiter, river gravel (Railway station Enschede, H.G.J. Schelling, 1950, situation 2009).



Figure 7.70 Combination of different coloured concrete, both in-situ and prefabricated (Schelling, 1952b): columns and beams of “grey” on-site concrete made with river gravel and Portland cement; prefabricated claustra with white small (5-10 mm) gravel and white cement; panels with broken ceramic and white Portland cement; ceiling with white small (5-10 mm) gravel and Portland cement; all surfaces, except for the rubbed down panels, were sand blasted (Railway station Hengelo, H.G.J. Schelling, 1952, situation 2009).

7.6 Facing concrete

The use of coloured constituents such as special aggregates, white cement or pigments, was more expensive than normal concrete, yet desired as the normal grey concrete was initially disliked for architecture. A practical solution to make coloured concrete while reducing the costs was to limit the use of coloured concrete to the outer 3–5 cm of a concrete element. Contrary to a decorative plaster (see Section 7.3.1), which was applied on the concrete afterwards, facing concrete (*voorzetsbeton*, *sierbetonlaag*, *edelbeton*) is poured together with the main concrete. This technique played an important role for exposed concrete and natural stone imitation at the beginning of the 20th century. It was commonly applied in other countries, such as Germany and the United States of America (Marsh, 1904; Petry, 1913; Von Mecenseffy, 1911). Petry (1913) described a number of German buildings where this technique had been applied, including the concrete mixes used. In the Netherlands, the use of facing concrete increased together with the growing use of natural stone imitations (Van der Schrier, 1938).

The technique of facing concrete was commonly discussed in Dutch textbooks (Bergsma, 1934; Petry, 1913; Roelofsen, 1940; van den Berg, 1961; Van der Kloes, 1908c; Van der Schrier, 1938, 1942, 1951, 1960, 1968; Verhey, 1912; Wattjes, 1931, 1943). Facing concrete was produced both in-situ and prefabricated, the latter commonly for natural stone imitations and decorative concrete. When used in-situ, the coloured concrete was poured simultaneously with the structural concrete. A mixing of the two concretes was prevented by placing a metal shutter between the two mixes while pouring. This shutter was slowly pulled upwards during compaction to achieve a good cohesion between the two layers (Figure 7.71). It required several lifts to achieve a good compaction and to avoid a later mixing of the two concrete species, causing several construction joints. In case of prefabrication it was possible to rotate the concrete element in such a way that first the facing concrete could be poured, compacted and applied on top the backing concrete (Figure 7.72). The theoretical technical advantage was that the coloured concrete and the filling concrete would behave as one material, and not detach as it was known from plasters on concrete. The technique could be applied for reinforced and for plain concrete. The surface of the facing layer could be treated as normal concrete, and was often tooled.

Concerning the mix design of the facing layer, it was advised to use a rich and plastic concrete (Von Mecenseffy, 1911), or contrary a dry mix (Van der Schrier, 1960); more precise were advices to use a relative high cement content of 400 kg/m³ (Roelofsen, 1940), which can be influenced by the common use of smaller coarse aggregates. To avoid damages, it was advised to ensure that the backing and facing concrete had a similar shrinkage, which should be confirmed by tests. Yet, concerns about the durability of such composite constructions made from two different concrete mixes were expressed. Van der Kloes (1908c) and Wattjes (1931) doubted the durability as the two layers would have a different shrinkage, causing a

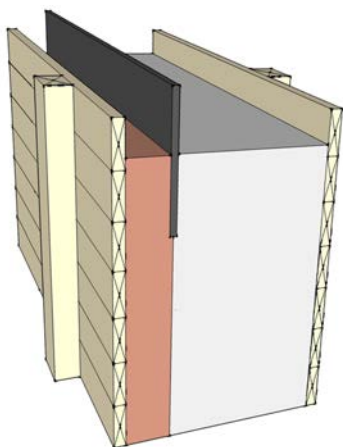


Figure 7.71 Schematic drawing of pouring of a facing concrete. During pouring, a mixing of the facing concrete (red) and backing concrete (grey) is prevented by a metal shutter, which is pulled carefully upwards during compaction.



Figure 7.72 Section through a prefabricated window sill with clearly visible ca. 2 cm thick facing layer and a reinforced backing concrete (1930s housing, The Hague).



(a)



(b)

Figure 7.73 Detail of a column base made from decorative concrete (Main entrance Blijdorp Zoo, Rotterdam, S. van Ravesteyn, 1939-1941, situation 2011). a) Overview of the column base, cracked at the top right corner. b) Detail spalled and cracked concrete, exposing the interface between facing and backing concrete (arrow).

detachment of the facing concrete, which was intensified with the impact caused by tooling the surface. Gratama (1916) confirmed these doubts and admitted that the experience with facing concrete had not always been positive. It was not considered impossible to achieve good results, but it required a careful execution (Wattjes, 1931).

The construction of a concrete out of two different layers can affect its durability as, depending of the differences of cement and aggregate type, the properties of the two concretes can differ. Roelofsen (Kraaijvanger, 1962; v.d.V., 1962) saw the main disadvantage in the use of the sliding shutters and problems with the bond of the two layers and possible unequal shrinkage. A rather thick, unreinforced facing layer can be exposed to (thermal) stresses, causing cracking. The concrete cover can sometimes be too little if the facing layer is reinforced, making the concrete more vulnerable for corrosion. The construction method can be the source of deterioration as well; the sliding shutter could complicate compaction, for example if the distance between the shutter and reinforcement was little. The amount of lifts required for good compaction created more joints, which can be weaker points of the construction.

Dutch examples of the use of facing concrete in-situ are mentioned in literature. An early example was a railway bridge in Arnhem dating from 1909, the *Zijpendaalsche poort*. It is written that the façade of the bridge was made with a facing concrete (*bekleedingsbeton*) with a “fine terrazzo”, which was cast together with the structural concrete and afterwards sanded (Muller, sa). However, as the bridge has been demolished recently, verification on-site is not possible.

In another case, reviewed literature indicates the use of a facing concrete for the Z.H.E.S.M. Hofplein railway viaduct in Rotterdam (for example Van Zutphen, 1958); Van der Kloes described the poor quality of the facing concrete of a Z.H.E.S.M structure, yet did not mention which structure (Van der Kloes et al., 1924). Other, earlier references mention the use of a decorative plaster, a *kunstzandsteen*, (Bergsma & Homan van der Heide, 1910b; Braak, 1907). Indications from a visual inspection and microscopy of samples (see Figure 7.25 and 7.26) of the viaduct are that a decorative plaster was applied and not a facing concrete; the texture made by tooling indicates a treatment of a fresh plaster and not of a hardened concrete; yet due to the innovation of the project and changes in construction, a partial use of facing concrete cannot be exclude without further research.

Unambiguous is the use of facing concrete for prefabricated decorative concrete elements, especially from the 1930s on. Several examples, from fine architecture to mass housing from this period exist. The use of a facing layer can often be seen in damaged areas (Figure 7.73 to 7.76). As the use of a facing layer saves costs, it is still advised nowadays (Neville, 2008).

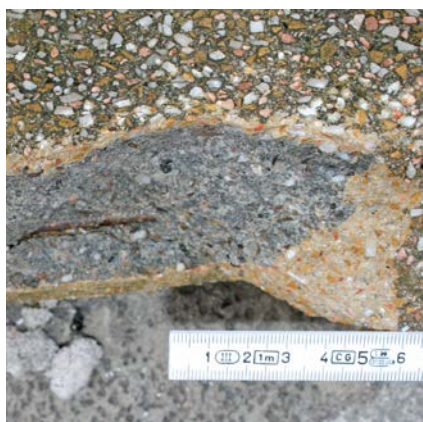


Figure 7.74 Detail of a demolished window sill showing a beige coloured facing layer with differently coloured aggregates and a grey backing concrete. Notice the colour difference between the weathered, soiled surface and the recently fractured surface (housing, Rotterdam, 1930s, situation 2010).



Figure 7.75 Decorative concrete element, due to damage of the facing layer and backing layer are visible; the facing layer was made with one type of small crushed stone; notice their greyer colour at the fractured surface (social housing, Rotterdam, M. J. Granpré Molière P. Verhagen, 1935, situation 2010).



(a)



(b)

Figure 7.76 Stair case made with prefabricated steps (Caballero factory, The Hague, 1953, F.A.W. van der Togt, situation 2009). a) Overview. b) The use of a facing concrete is visible at a damaged corner.

7.7 Decorative concrete

Decorative concrete (*sierbeton*) is not defined by a special production method, surface finish technique or material use. It is a concept of the aesthetical perfection of the originally engineering material concrete. It was seen as a decoration, an emphasis for the building, a ennoblement of the prosaic concrete with a surprising variety of “poetic” possibilities (Fernhout, 1957, pp. 103-104). With decorative concrete, the perception of concrete was redefined. It was neither a structural engineering material nor a substitute for natural stone, but a quality class of its own (van den Berg, 1961). However, its proximity to natural stone imitations in terms of material choice and tooling of the surface was criticised, making it difficult to distinguish between natural stone and decorative concrete (van den Berg, 1961). Schelling, an advocate of exposed concrete and explorer of possibilities to modify the constituents for aesthetical effects, strongly rejected decorative concrete, as it is a too artificial beautification of concrete and too close to the field of natural stone imitation (Schelling, 1950b). Ironically, particularly his already previously mentioned railway stations, especially Enschede, were used for advertisements for decorative concrete by the producer *De Meteor* (Figure 7.77) or named as example (Fernhout, 1957; Scharroo, 1951).

For decorative concrete the aesthetics were emphasised and not the structural benefits achievable with reinforced concrete. It is characterised by a conscious aesthetical choice and combination of aggregates, pigments, cement and surface finishes. It was manufactured as small prefabricated elements, as the high aesthetical demands were only achievable by prefabrication. For economic reasons, the technique of facing concrete (see Section 7.6) was commonly applied for elements thicker than 4 cm.

The production of decorative concrete started in the 1930s. Many factories producing it, for example the Dutch company *De Meteor*, originated in the production of prefabricated concrete elements such as concrete pavers (Anon., 1934; de Beukelaer, 2007; Fernhout, 1957). Exploring new fields of application for prefabricated concrete elements and inspired by achievements abroad (e.g. Germany), they started to produce decorative concrete (de Beukelaer, 2007).

Decorative concrete was sold under brand names, which distinguished themselves by the aggregates used and the surface finish. The main brands were *Artilux*, *Artistone*, *Colcret* and *Ocraat*. *Artilux* was made with crushed *Petrosilex*, a composite material made from different metallurgical slags, and was available in several colours, and advertised for its durability. It was produced by *N.V. Beton-industrie v.h. Ald. Van Bodegom en Co.* and by *N.V. Betonbouw v.h. Kool en Wildeboer*. Other brands used crushed granite, namely *Artistone*, produced by *De Meteor*, *Colcret*, produced by *N.V. Wernik's Betonmaatschappij*, and *Ocraat* and *Ocraatine* produced by *N.V. Ocraat en Ocraatine*. The difference between *Ocraat* and *Ocraatine* was that the first was chiselled, point tooled or bush hammered, whereas the latter was sand blasted (Bonnema & Vegter, 1946). In general, common surface

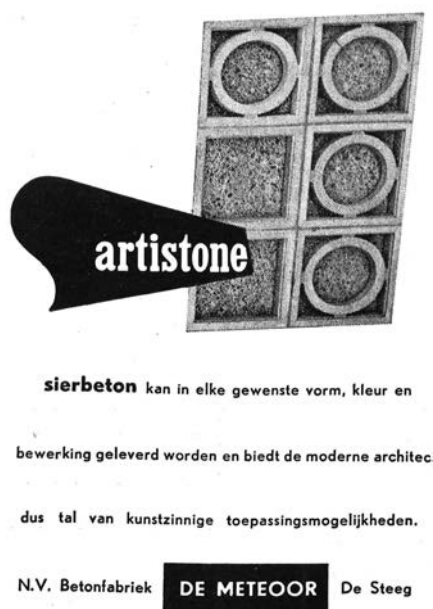


Figure 7.77 Advertisement for the decorative concrete brand *artistone* by *De Meteor* in the *Journal Cement* (1951), showing panels and claustra used for the railway station in Enschede by H.G.J. Schelling (see Figure 7.44).

finishes were washing out of the cement film, polishing, and tooling. Looking at the aggregates used, a wide variety can be found: often granite, sometimes gravel, quartz, basalt, porphyry, lime stone, and broken ceramic materials (e.g. stone ware, tiles, bricks, glass) (Bond van Fabrikanten van Betonwaren in Nederland, 1957, 1964) White cement was used often, sometimes coloured with pigments.

Common decorative concrete elements were balustrades (Figure 7.78), column bases (Figure 7.73), flower pots, claustra (Figure 7.70), façade decoration (Figure 7.79), window sills (Figure 7.35), capitals, columns, cornices, monuments, pergola, plinths, and tiles (Anon., 1934; Bond van Fabrikanten van Betonwaren in Nederland, 1957). Besides mass produced decorative concrete elements, customised decorative concrete elements were produced (Figure 7.80). Many large scale post-war buildings made with prefabricated coloured concrete elements were made by Artistone (Figure 7.81 and 7.82). Differences can be seen in the way the decorative concrete was artistically approached; one option was to combine individual concrete elements, and textural and colour differences were per element, as the works of Schelling show. A different approach was to use an entire façade as a canvas on which an artist would “paint in concrete”; the prefabricated panel sizes would not necessarily correspond with the drawing and multiple colours would be used on one panel. Examples are the former *stationspostkantoor* in Rotterdam (Figure 7.82) and the former Grotius lyceum in The Hague (Figure 7.15).



Figure 7.78 Decorative concrete balustrades (Zoo Blijdorp, Rotterdam 1939-1941, situation 2010).

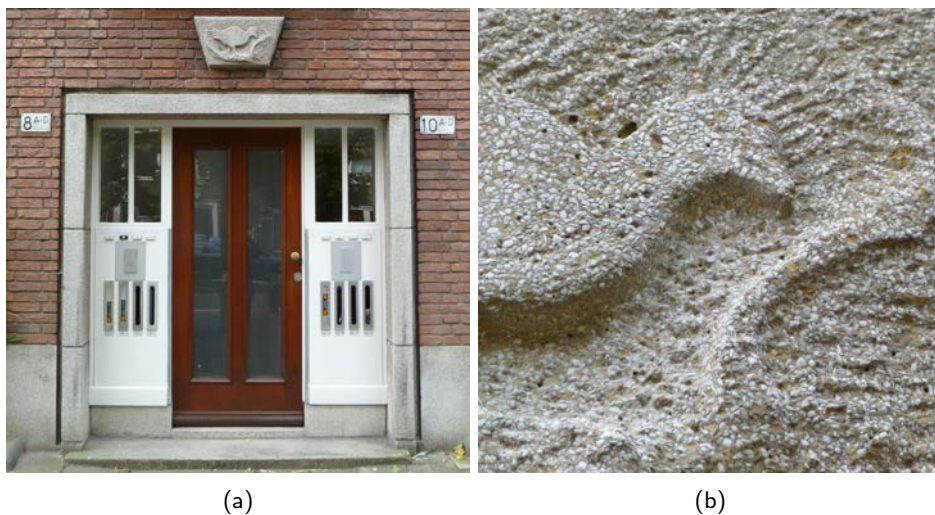


Figure 7.79 Example of small decorative concrete elements (housing, Rotterdam, architect and exact date unknown, 1930s, situation 2011). a) Overview entrance with decorative concrete plinth and sculpture above door. b) Detail of decorative stone above the entrance.



Figure 7.80 Example of a sculpture in decorative concrete, combining red and green concrete (former Giraffe compound, Zoo Blijdorp, Rotterdam, S. van Ravesteyn, 1939-1941, situation 2010).

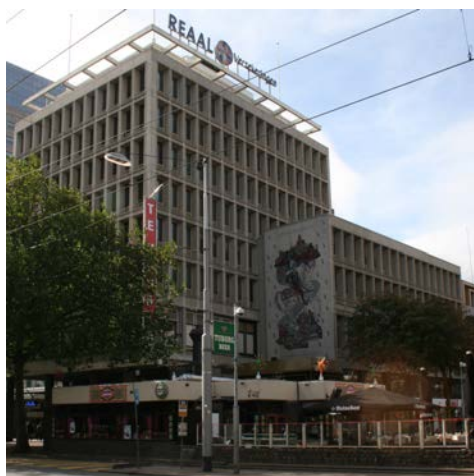


Figure 7.81 Office building made with Artistone panels (Holbeinhuis H.A. & H. M. Kraaijvanger, Rotterdam, mosaic made by L. van Roode, 1951-1954, situation 2009).

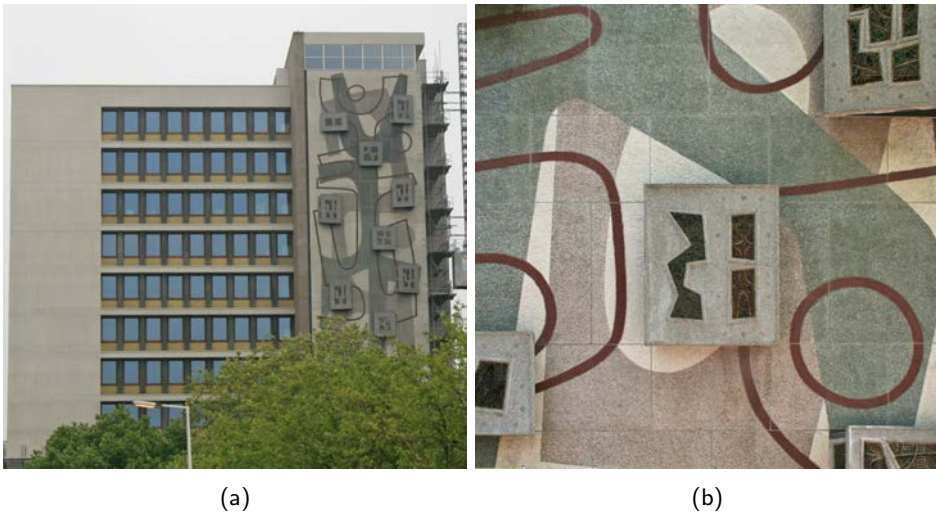


Figure 7.82 Façade made with Artistone elements (Stationspostkantoor Rotterdam, E.H.A. & H.M. Kraaijvanger 1954-1959, situation 2009). a) Overview. b) Detail of Artistone elements and concrete windows.

As the elements are mechanically compacted either with tamping irons or, in case of mass fabrication, with vibrating tables, a dryer concrete mix with less mixing water could be used, reducing the water/cement ratio (w/c ratio) to 0.3 – 0.35, which was considerably lower than for in-situ concrete. It was also advised to use a lower w/c ratio for the backing concrete than for the facing concrete; the backing concrete would withdraw some water from the facing concrete and thereby reduce the amount of the shrinkage cracks on the facing concrete. The elements were commonly reinforced because of the stresses caused during the finishing of the surface, transport and assembling. The elements could either be cured normally or steam cured to reduce the curing and hardening time (van den Berg, 1961).

7.8 Conclusions

In this chapter it was shown that the surface finish of historic concrete varied during time. The chosen technique was influenced by the typology of the building, the social acceptance of concrete as an aesthetic material and the progress of concrete technology. Understanding the historical context can help to identify whether the surface finish was consciously chosen or if it was a common technical solution of the time (see Figure 2.17 *Timeline for surface finishes applied to historic concrete*). Additionally, more awareness is necessary to the fact that the aesthetical treatment of the surface was already early important when the surface was exposed to the public eye and many techniques were earlier applied than commonly assumed.

The assumption that all concrete is grey cannot withstand. Compared with other countries, a knowledge and material transfer from the neighbouring countries can be observed again in the Netherlands.

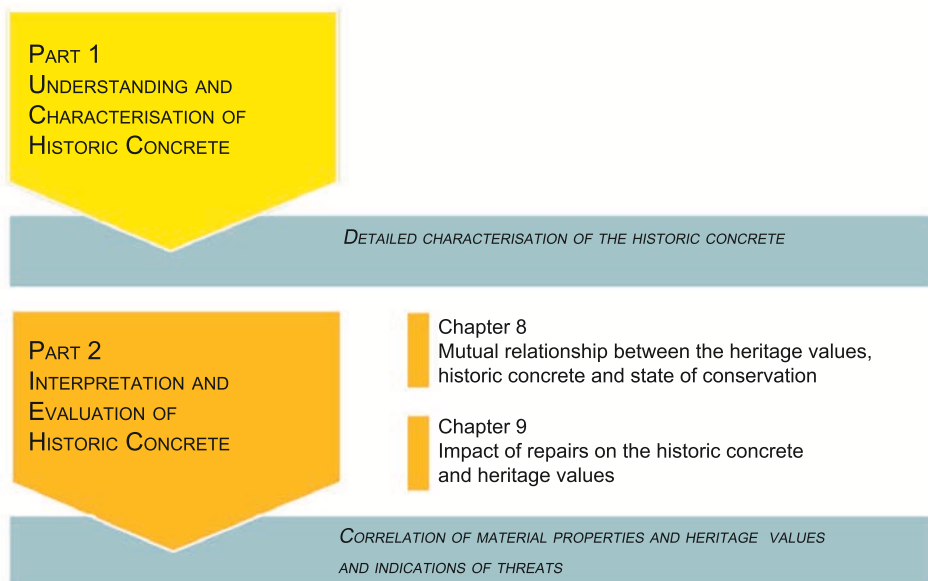
When investigating the surface finish of historic concrete, the original surface cannot always be identified directly, as many surfaces have been painted, plastered or otherwise been altered during interventions. Textural details might have been lost due to weathering, and as a side effect changing the colour of the concrete as more aggregates are exposed. Soiling, efflorescence and washing out and fading of pigments can alter the (original) colour of a concrete. In such cases, the investigation of the surface in more protected zones, for example under window sills, might give a better indication for the original surface texture or colour. Detailed material research on the constituents used such as possible pigments, aggregates, or uncommon techniques such as metallisation, is advisable to understand how the colour was achieved and as orientation for possible repairs (e.g. colour of a repair mortar). Especially for metallisation, little is known of how it was done in detail and how to recognise it in the field; more reference data and objects are needed, including possibilities to repair or reproduce such surfaces. Yet, also more common techniques where the main variations lay in the binder and aggregates used, such as the concrete used by Schelling, can challenge common repair techniques and would require detailed material pre-investigation.

Concluding, the way historic concrete was made, which constituents were used, and how it appeared are closely related. A sound understanding of these relationships is required when trying to identify and characterise historic concrete. In this first part of the thesis, these relationships were shown and the historical context outlined which give guidance when trying to identify historic concrete, both technically and historically. It was also shown that the development of concrete underwent several and sometimes quick changes, leading to a great variety of concretes in a short period of time. This includes phases of trial and error, and only short use of some techniques and materials. Their correct identification is relevant to clarify the Dutch history of concrete technology and application.

In the following Part II *Interpretation and Evaluation of Historic Concrete* it will be shown that a detailed characterisation of the historic concrete is essential for the entire conservation process in order to preserve the historic concrete and the ascribed heritage values adequately.

Part II

Interpretation and Evaluation of Historic Concrete



Part outline

In Part I *Understanding and Characterisation of Historic Concrete*, the required background knowledge for concrete conservation, namely the construction history and proprieties of historic concrete used in the Netherlands, was discussed. This allows an understanding and characterisation of historic concrete during conservation processes and historical investigations. In the succeeding step, it is necessary to interpret and evaluate the historic concrete; this will be discussed in Part II.

For conservation, two main types of assessments of historic concrete are carried out: that on the state of conservation and that on heritage values. The information gained is later used to plan and evaluate interventions, if any. However, in current practice, technical aspects and heritage values are usually not combined in the investigation and decision-making process. As a result, heritage values are endangered, as it is not understood which material aspects are relevant for their preservation. This includes the impact of both degradation and repair techniques on the historic material and the heritage values, an aspect that is seldom analysed due to the separation of the fields of construction history and technical investigations. To improve the conservation process, a systematic cooperation between the different fields and a combined analysis of technical and historical surveys is suggested. By this, the mutual relationship between heritage values, the historic material and the state of conservation can be identified and potential threats towards the heritage values and the material evaluated. With the obtained knowledge, the boundary conditions for conservation strategies can be outlined, which will be discussed further on in Part III.

Chapter 8

Mutual relationship between the heritage values, historic concrete and state of conservation

Chapter Outline

In Part I of this thesis, the background knowledge on construction history was given to characterise historic concrete. In the following step, it is necessary to interpret and evaluate the historic concrete; in practice this is done in form of technical surveys and value assessments. However, the data of both assessments is not combined and decisions are not based on both aspects, heritage values and technical performance. Without understanding the mutual relationship between the heritage values, historic concrete and state of conservation, the preservation of heritage values cannot be systemically integrated in the conservation process.

In this chapter, the mutual relationship between heritage values and historic concrete will be discussed, and reviewed whether present degradation is either a threat or an expression of heritage values. The chapter concludes with three case studies - Fort Bezuiden Spaarndam, Hofplein railway viaduct and the earth retaining walls of the Groot Museum - where the correlations will be illustrated.

8.1 Introduction

The preservation of a (listed) historic building together with the ascribed heritage values is a main aim of conservation (for example ICOMOS 1964; 2003a). Heritage values characterise the significant aspects of a monument for society and outline why a building should be preserved and listed. Depending on the cultural context

of a society, the types of heritage values may differ. In the Netherlands, they are determined by a value assessment which is based on historical surveys (Guidelines for Building, 2009; Richtlijnen bouwhistorisch, 2009).

Heritage values ascribed to historic concrete structures are endangered or even lost in case insufficient awareness exists to integrate them into the conservation process. The threats can be external, and sometimes obvious such as the threat of demolition, yet they can be also inherent to the concrete; for example, a too high amount of calcium sulphate in early concretes, added to control setting, can initiate degradation. An underlying problem lies in the conservation process itself, because no analysis is carried out if and in which way the heritage values are related to the historic material. Yet, to be able to preserve the heritage values, the mutual relationship between abstract heritage values and the historic concrete has to be determined. Otherwise, it cannot be evaluated whether the heritage values are either endangered or enhanced by an intervention or by degradation.

To understand the mutual relationship, sufficient data about the heritage values, the construction history and material properties should be available and analysed together. From concrete conservation projects studied during this research, it was seen that in practice technical and historical information were rarely available at the same time during the conservation process. Additionally, guidance was lacking for an appropriate intervention balancing the amount of historic material to be removed and the durability of the intervention. Noticeable was that often neither the underlying cause of damage, nor the specific properties of the historic concrete, nor the compatibility of the chosen repair technique had been investigated. Consequently, repairs fail prematurely, heritage values are lost by removing valuable parts of the historic concrete or covered with new repair material.

To improve the concrete conservation process, it is necessary to give guidance on the criteria to develop and evaluate a conservation strategy. As a prerequisite, stakeholders should be convinced of the benefits of carrying out the required research prior to the start of the construction works. Practical problems are the different ways the surveys are carried out and the almost systematic absence of any integrated analysis of the obtained information. For value assessment, no uniform methods exist in Dutch practice. The level of detail of (construction) historical surveys strongly depends on the historian and type of assignment. An obstacle is that most value assessments and underlying historical reports remain at an abstract and general level and do not go into the required level of detail. Detailed information on the ascribed heritage values is however relevant as reference for the development and evaluation of different conservation strategies and their impact on the heritage values (Heinemann, Zijlstra, van Hees & Nijland, 2011).

Not less important is the consideration of the heritage values during the inspection of the state of conservation (Heinemann, 2007). If technical surveys are carried out to determine the presence and cause of damage, they usually focus on safety, structural and economical aspects as these are the main criteria on which repair strategies are based. Specific aspects of historic concrete are not mentioned, unless they are a cause of damage.

As the preservation of heritage values is the main objective of conservation, their possible endangerment should be investigated as well. Interventions should not only be initiated to treat or prevent degradation but also when heritage values are endangered. A combined analysis of the construction history, heritage values, and state of conservation can help to determine the mutual relationship of heritage values to the material, creating a sound basis for the conservation process. This requires, however, detailed pre-investigations and sufficient background knowledge (Heinemann, 2008b,c). Such an analysis gives increased insight in whether assumed degradation and related symptoms possibly express part of the heritage values, requiring a different technical approach. With a sound understanding of which material characteristics represent heritage values, the impact of different repair techniques on both the historic material and heritage values can be evaluated; this will be addressed in the following chapter.

However, before discussing the relationship between heritage values and materials in Section 8.3, the different types of heritage values applied in the Netherlands will be introduced in Section 8.2. The mutual relationships between these heritage values, state of conservation and historic concrete will be discussed in Section 8.4 and illustrated by three cases: the Fort Bezuiden Spaarndam (1897-1901, Section 8.5), the Hofplein railway viaduct (1900-1908, Section 8.6) and the earth retaining walls of the unfinished Groot Museum (1921, Section 8.7). Methods of determining heritage values and the underlying philosophical discussions will not be discussed in further detail, as this is a research field on its own. Instead, the practical use of heritage values once defined will be addressed; it will be shown how they can be integrated in the conservation process. Likewise, degradation mechanisms of concrete will not be addressed in detail. For this, several reference works exist which will be known by technical specialists.

8.2 Categories of heritage values

Societies decide to preserve historic structures to connect themselves with their past, to express their identity and to be witness of former periods. To select which objects are worth of protection, heritage values are determined and used as selection criterion. Heritage values are not a property of the material or object but an interpretation by a society or person of the material, object or building (see for example Appelbaum, 2009). Heritage values can change during time, influenced by insight gained, cultural changes, and alterations of the building. For conservation, objective heritage values should be used and not subjective. This means that a building should be evaluated in a cultural context (for example similar objects, period, social significance) and not by the memories or preference of individuals.

To assess objectively the cultural-historical value of a material/building is not as straightforward as it is to determine its technical condition. Heritage values are descriptive and qualitative, which makes it difficult to evaluate when they are endangered. It is therefore even more important that the parties involved

understand the heritage values ascribed to the historic concrete for sound decision-making in the conservation process.

In the Netherlands, different sets of heritage values are used for the value assessment of heritage structures. An overview of the heritage values addressed in different documents is given in Table 8.1, where the *Monumentenwet 1988* (Dutch Monuments and Historic Buildings Act 1988; 2011) forms the basis. The list has been extended by the Dutch heritage care authorities for the selection of buildings from the period from 1850-1940 (RDMZ, 1991) and adapted for construction historical surveys (Richtlijnen bouwhistorisch, 2009). For Dutch UNESCO World Heritage Sites, international guidelines apply as well (ICOMOS, 1994; UNESCO, 2008). In practice, the categories are not always applied strictly; in construction historical reports and value assessments, additional or modified heritage value categories can be encountered. It is outside the scope of this thesis to explain in detail the different types of heritage values but it will be explained which categories of heritage values are more often related to historic concrete.

The heritage values of historic concrete are mainly discussed in context of preserving buildings from the Modern Movement and of the Post-World War II period. Hereby, traditional approaches of value assessment and applicability of conservation charters are often questioned. Arguments put forward to justify a different approach are, for example, the number of buildings, the changes in construction techniques, increased importance of the intention of the architect, the performance, viability and appeal of the building (Saint, 1996). Reluctance for listing is the fear of “freezing” buildings, hindering transformations and re-use; practical problems are that conservation of these buildings might be too costly and too complicated (Cherry, 1996).

Specific categories of heritage values are questioned for more recent heritage, especially those related to construction methods, materials and uniqueness. Arguments that the value of craftsmanship is not suitable for Modern Architecture are the changed construction process, and increased industrialisation and standardisation, implementing a lack of history and technological progress (Prudon, 2008). Less discussed are possible changing characteristics of heritage values, caused by new construction methods, the technological progress of prefabrication and its influence on building, material choice, society and cities; details of technological progress may be overgeneralised and specific characteristics of the 20th century construction techniques less known.

Particularly the intention of the architect has been emphasised for recent architecture, often justifying the removal of later additions and a reconstruction to the state of the building after completing the original works. A sacrifice of the historic material is seen acceptable to preserve the ideas of the architect’s design intent (Prudon, 2008; Saint, 1996). Such concepts can imply an overlooking of the role of the (often anonymous) architect and builders from previous centuries and their certainly present design intent, and provoke the idea that conservation is only about freezing buildings to the state after construction.

Table 8.1 Overview of categories of heritage values officially used in the Netherlands.

National heritage values	
Monumentenwet 1988 (Ministerie voor Onderwijs Cultuur en Wetenschap, 1988)	
Aesthetical values	<i>Schoonheid</i>
Scientific significance	<i>Betekenis voor de wetenschap</i>
cultural-historical value	<i>Cultuurhistorische waarde</i>
Monumenten Selectie Project (MSP) (RDMZ, 1991)	
Values from the Monumentenwet 1988 plus the following, additional values:	
Uniqueness	<i>Zeldzaamheid</i>
Integrity and recognisability	<i>Gaafheid en herkenbaarheid</i>
Values of building groups	<i>Ensemblewaarden</i>
Architectural historical values	<i>Architectuurhistorische waarde</i>
Richtlijnen Bouwhistorisch Onderzoek (Guidelines for Building Archeological Research) (Guidelines for Building, 2009; Richtlijnen bouwhistorisch, 2009)	
Architectural historical values	<i>Architectuurhistorische waarde</i>
General historical values	<i>Algemene historische waarden</i>
Ensemble values or urbanistic values	<i>Ensemblewaarden</i>
Building archaeological values [sic]	<i>Bouwhistorische waarden</i>
Values based on the history of use	<i>Waarden vanuit de gebruikshistorie</i>
International heritage values	
NARA (ICOMOS, 1994)	
<i>Authenticity</i>	
<i>form and design</i>	
<i>materials and substance</i>	
<i>use and function</i>	
<i>traditions, techniques and management systems</i>	
<i>location and setting</i>	
<i>language, and other forms of intangible heritage</i>	
<i>spirit and feeling</i>	
<i>other internal and external factors</i>	
UNESCO Operational Guidelines (UNESCO, 2008) (extract)	
<i>Universal value:</i>	
<i>(i) represent a masterpiece of human creative genius</i>	
<i>(ii) Exhibit Interchange of human values [...] on developments in architecture or technology [...]</i>	
<i>(iii) Bear a unique or at least exceptional testimony to a cultural tradition which is living or which has disappeared</i>	
<i>(iv) Be an outstanding example of a type of building, architectural or technological ensemble [...] which illustrates (a) significant stage(s) in human history</i>	
<i>(v) Be an outstanding example of a traditional human settlement, [...] which is representative of a culture [...] or human interaction with the environment [...]</i>	
<i>(vi) Be directly or tangibly associated with events or living traditions, with ideas, believes, with artistic and literary works [...]</i>	
<i>Condition must be of integrity and/or authenticity as defined in NARA</i>	

Such practice is at odds with international conservation charters in which reconstruction is considered undesirable and the history of a building, with all consecutive periods of change and modification, is valued (e.g. Australia ICOMOS, 1999; ICOMOS 1964,2003a). A cause for the shift of attributed values of the recent heritage is that its preservation was initiated by an architectural historical interest in saving the oeuvre of famous 20th century architects. Organisations such as DoCoMoMo were founded in this context (Prudon, 2008).

A controversial value of recent heritage is the age value, meaning it is appreciated that a building looks or is old, a value very often understood and appreciated by laymen (Appelbaum, 2009; Riegl, 1996). Evidence of age can be valuable to understand that a building has a history. The age value can be reflected in many ways, varying from the application of styles or discontinued construction techniques, to traces reflecting the building's "life and age"; this can include alterations, deposits on the surface, weathering and erosion of materials, which are all processes which require time. A pristine appearance of an old building is sometimes considered as contradicting the age value. For traditional monuments, signs of ageing are commonly accepted. For more recent monuments, signs of ageing are more debated (Prudon, 2008). Especially symptoms affecting the appearance (e.g. soiling, biological growth) are often undesired. One reason for rejecting ageing symptoms is that the original appearance of 20th century buildings is well documented and the architect's original design intent is considered of importance.

A biased selection of heritage values does not only exist for Modern Heritage. It is a common misconception that heritage values are mainly related to aesthetics, as outlined by the ICOMOS Charter *Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage* (2003a, art. 1.3), where it is stated that the "*value of architectural heritage is not only in its appearance, but also in the integrity of all its components as a unique product of the specific building technology of its time.*"

Careless demolition and replacement of historic concrete can falsify the history of a building and the history of concrete in general. The function of the original material as an on-site archive is hereby often ignored and endangered. An argument too often put forward for reconstruction is that sufficient documents exist to make a copy (Prudon, 2008). Even when making a copy would be accepted as a justified act of conservation, the construction history of concrete makes clear that it will not always be possible to recast the original concrete due to changes in production and design.

The review of the construction history of the late 19th and 20th century has only started recently and knowledge has not been sufficiently disseminated. This hinders the assessment of heritage values related to the historic materials of this period. Cherry (1996) identified these problems as well, making it difficult to place buildings in the correct historical context, and more information is necessary to understand the new types of monuments.

In Part I of this thesis, it has been shown that, in the case of historic concrete, changes in the use, appreciation and composition of concrete have taken place over

time and specific characteristics of different periods can be identified. Concrete is an artificial material and sometimes industrially mixed; variations and conscious modification changed the appearance and the performance of historic concrete. It should not be forgotten that historic concrete did not only play a role in Modern Architecture. For example, very early historic concrete is usually found in military and civil engineering structures. Here, new building technological developments were introduced for the first time. Therefore, when encountering historic concrete, the scientific significance, the cultural-historical values, uniqueness, general historical values, construction historical values, and the influence of concrete on the aesthetical values should be reviewed in more detail, as these are commonly not recognised due to limited background information.

Regardless whether the emphasis of the conservation aim will be the design intent or the original material, it is necessary to understand historic concrete as a material subject to technological development as a basis for the decision making process, in order to safeguard any heritage values related to the original material.

8.3 Mutual relationship between heritage values and historic concrete

Heritage values are in practice often too abstract to allow an implementation of their preservation in (technical) discussions. To integrate their preservation in such discussion and resulting decision making, the more abstract heritage values should be translated first to tangible material properties and material-related variables. This means it has to be analysed which material variables contribute to the heritage values. Understanding the mutual relationship between heritage values and material is necessary for identifying risks towards heritage values and material, and to evaluate possible interventions.

In a second step, it has to be determined how the material properties representing the heritage values were achieved and which aspects were consciously modified or commonly applied. Together with further material and historical research, these questions can be answered. Hereby, the timelines given in Section 2.3 *Historical context and material properties* can give more information of the historical context and the respective chapters of the first part of this thesis may provide detailed material historical information.

For example, aesthetical values can relate to the appearance of the historic concrete, the proportions of the concrete element, and the surface finish, including colour and texture. The appearance of the concrete could have been influenced by the used cement, aggregates, pigments, or painting, and the texture achieved by tooling, formwork imprints, or rendering. From the historical context (see Figure 2.17 *Timeline for surface finishes applied to historic concrete*), it should be understood whether the surface finish was typical for the building typology and the techniques available in that period to alter the surface.

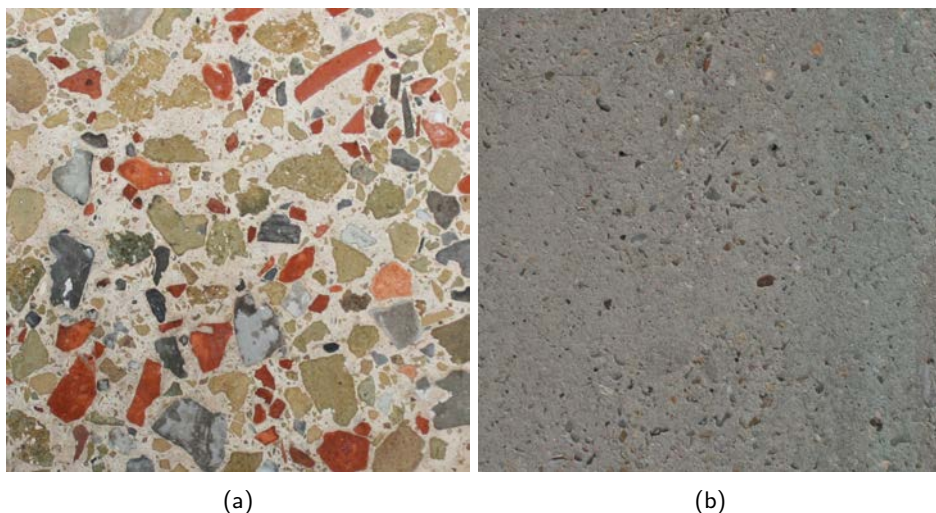


Figure 8.1 Two exposed concrete surfaces with a smooth texture from the same period. a) Polished surface, concrete made with white Portland cement and differently coloured crushed bricks (Railway station Enschede, 1950, H.G.J. Schelling, situation 2009). b) Smooth surface texture made by using triplex formwork; during the restoration (2001-2005), later applied layers of paint were removed; normal concrete with Portland cement and gravel (Groothandelsgebouw, Rotterdam, H. Maaskant & W. van Tijen, 1950, situation 2008).

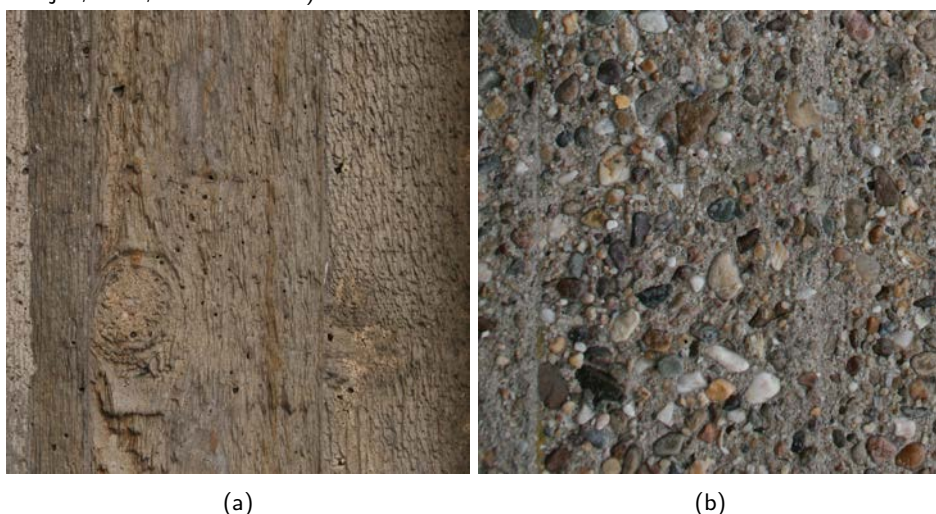


Figure 8.2 Two differently textured exposed concrete surfaces of the same building (Pumping station Parksluizen, Rotterdam; G. J. van der Grinten, 1967, situation 2007). a) Still visible details of timber formwork in protected areas. b) Textural details have eroded, exposing the aggregates and changing the colour of the concrete.



Figure 8.3 Example of a modified surface: the original surface was sand blasted, but has been covered with a render with pebbles, and with local later repairs and spalling (office building *De Nederlanden van 1845*, The Hague, H.P. Berlage; 1921 -27, situation 2009).



Figure 8.4 Example of an intervention: the column was made with consciously chosen constituents; the aggregates are exposed to modify the texture and colour, resulting in a brownish multi-coloured appearance, whereas the intervention (footing) is light grey and smooth (railway station Zutphen, 1952, H.G.J. Schelling, situation 2009).

For example, the two exposed concrete surfaces in Figure 8.1 are both smooth and from the same period, but the used technique was different; in one case exposing the aggregates (Figure 8.1a), in the other not (Figure 8.1b). Not only the original surface finish should be considered, but also the signs of ageing, degradation and weathering, and previous interventions (Figures 8.2 and 8.3). These should be evaluated whether they represent aesthetical values, have no impact or are rather a threat. Figure 8.2 shows two differently textured exposed concrete surfaces of the same building; the textural details of timber formwork are still visible in protected areas, whereas in the exposed areas these have eroded, exposing aggregates and changing the colour of the concrete.

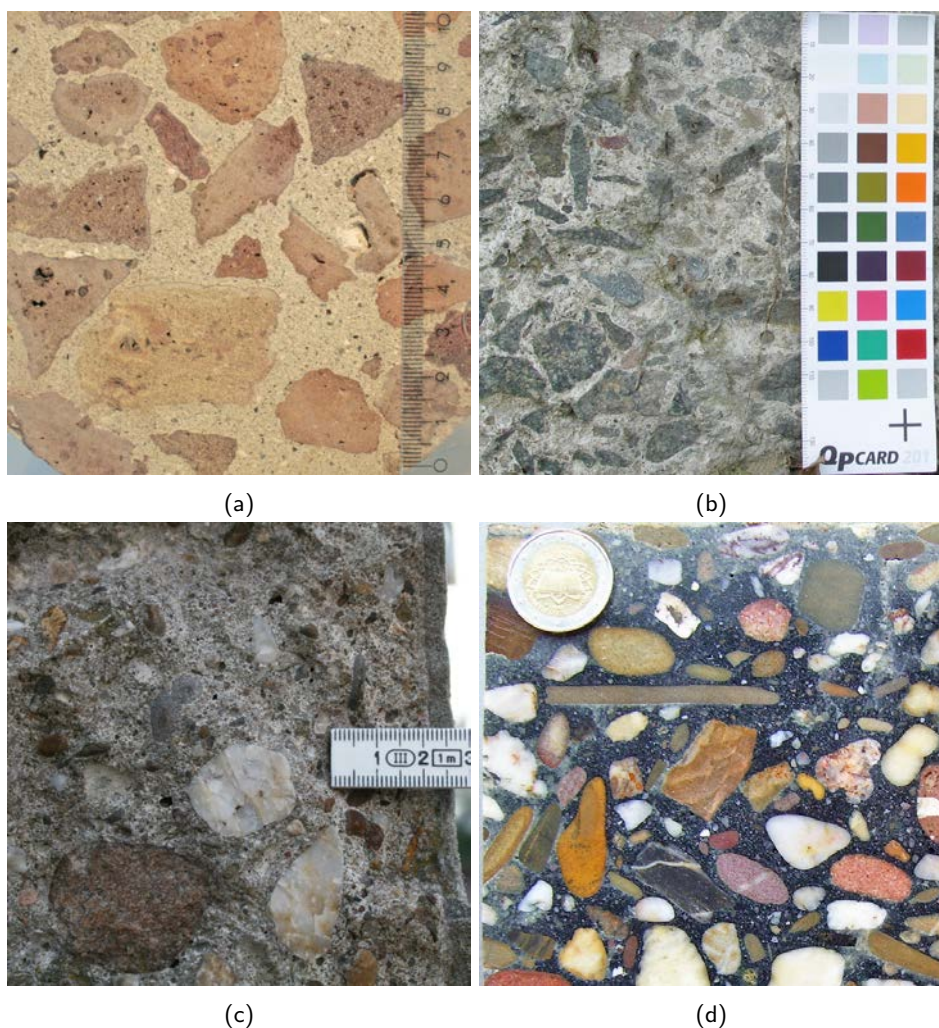


Figure 8.5 Example of aggregate types, sizes and grading reflecting the state of the art during construction time. a) Brikkonbeton with large aggregates (broken brick) and no middle fraction (military building, middle 19th century). b) Crushed stone (porphyry from Quenast) with no middle fraction (Fort Vijfhuizen, 1899, situation 2006). c) Use of gravel and different fractions but not well graded (St. Jobsveem, Rotterdam, J.J. Kanters, 1912, situation 2010). d) Use of gravel and gap-graded concrete reflecting contemporary insight into mix design and technological progress (water cellar below J. Daniel Meyer plein, 1936, picture Timo G. Nijland).

For scientific and cultural historical values, the original historic concrete can be important evidence of a historically relevant period or event, or represent a step in concrete technology. For this, it should be understood which constituents, techniques and theories were commonly applied in a specific period. In Figure 8.5, examples are given on the changes regarding aggregates and grading: two 19th century plain concretes structures with angular aggregates and no middle fraction (Figures 8.5a and 8.5b), and two examples of reinforced concrete made with gravel, one with different fractions but no explicit grading (Figure 8.5c) and an early example of gap-graded concrete from the 1930s (Figure 8.5d).

Less obvious are any interpretations of values related to authenticity as the definition of the latter is heavily discussed and can have many dimensions, as shown by the *Nara Document on Authenticity* (ICOMOS, 1994, see also Table 8.1). Although commonly encountered in practice, authenticity is not listed as a category of heritage values in the Netherlands, except in connection with UNESCO World Heritage sites. Two common interpretations of authenticity are the presence of the original material or the original appearance of the building (Figure 8.6). For the first interpretation, changes occurred during time such as ageing or modifications to the building are often accepted or appreciated as long as the original material can be perceived. For the second interpretation, the original material is often considered less relevant as long as the original perception of the building is preserved or even reconstructed.

In Table 8.2, a summarised overview is given of possible material aspects which can represent heritage values. It has to be understood that the scale can vary, from the macro level such as an entire building or façade, to the element level, for example a column, and to the material level, including the constituents, and that these different levels are related. For example, the colour of a façade can be influenced by the used binder or added pigments. The time factor has also to be considered, as it has to be distinguished whether the heritage values originate from the construction period or from the time in service. Alterations should be reviewed, such as deposits, degradation symptoms (see the following section), previous repairs or interventions. The role of the historical context should be understood, as it influenced the material choice, design details and the way concrete was used. Examples for external factors are previous codes and standards, availability of materials, level of sophistication of concrete technology, appreciation and acceptance of concrete, existing construction methods, and historic events. Once it is understood and determined which variables of the historic concrete are relevant for the heritage values, is it possible to determine threats towards the historic concrete (Heinemann et al., 2011).

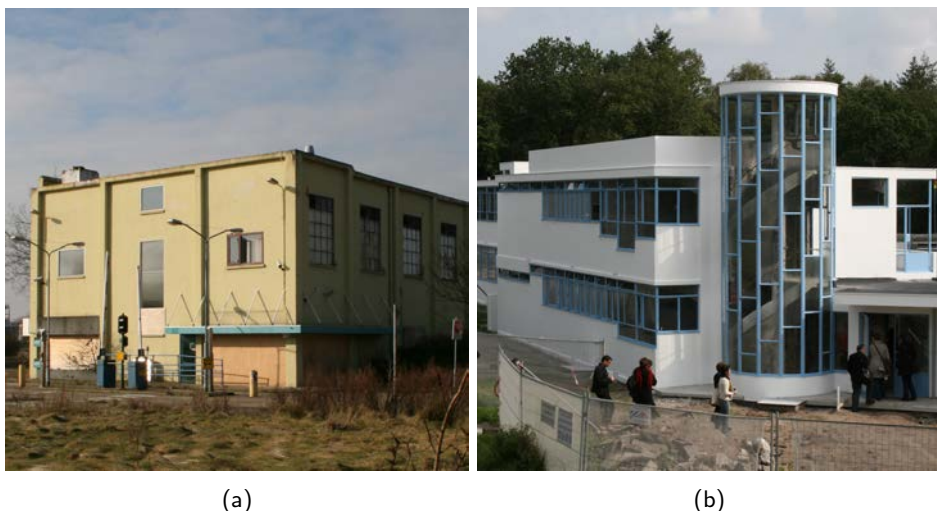


Figure 8.6 Two examples of buildings appreciated for the design yet with different approaches towards the original material. a) Earliest known remaining industrial building made as a monolithic Monier construction with changes during time still present (Calvé factory (*Moniergebouw*), Delft, 1905, situation 2010). b) Example of a restoration with partial reconstruction and emphasis on the architectural design intention (Dresselhuys pavilion, Sanatorium Zonnestraal, Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928, situation 2008).

Table 8.2 Overview of possible material variables and aspects of the historic context to which heritage values can be correlated.

Historic concrete	
Initial properties	
Design	Bulk/Constituents
• Structural	• Cement
• Architectural	• Aggregates
• Geometry of elements	• Pigments
Surface finish	• Mix design
• Texture	Reinforcement
• Colour	• System
• Tooling	• Ferrous metal type
• Formwork imprint	• Size and shape
• Cladding	• Position
• Render	• Connection
• Paint	
Alterations	
Deposits	
Degradation symptoms	
Signs of ageing	
Previous interventions and repairs	
Influence of the historical context	
Codes and standards	
Availability of raw material	
Level of sophistication of concrete technology	
Appreciation and acceptance of concrete	
Construction methods	
Historical events	

8.4 Mutual relationship between heritage values and the state of conservation

The relationship of heritage values with historic concrete is not limited to material aspects which originate from the construction period. Historic concrete will have undergone changes during time. Some changes are accepted as normal ageing processes whereas other changes are undesired and considered as degradation as they destroy the concrete or reinforcement, and thereby endanger the function and safety of the building. The degree of degradation depends on the material properties, the exposure class, external events, use and maintenance. Changes may have been caused by interventions and external events. These changes should be evaluated as they can either enhance the heritage values, be a value by themselves, or pose a threat towards the historic material and the ascribed heritage values. To identify possible correlations, surveys of the state of conservation should integrate both technical and cultural-historical aspects, or at least a cross-analysis of historical and technical surveys carried out. Otherwise, there is the risk that the preservation of values will be, intentionally or unintentionally, disregarded in the remaining intervention process. Before discussing how to correlate heritage values with the state of conservation in Section 8.4.1, it is necessary to address common practice of technical surveys carried out for conservation.

8.4.1 Technical survey of historic concrete in practice

The inspection of concrete structures is usually carried out by experts specialised in evaluating structural or durability aspects of (reinforced) concrete or the identification and cause of damages. Mainly infrastructure objects and buildings are investigated, in which most concrete dates from the second half of the 20th century, especially from the 1950s and 1960s. Technical assessments can be carried out at different levels of detail, from routine inspections, detailed inspections and degradation assessment. In technical surveys it is advised for purposes of clarity to only document the main damages. A definition of a main damage is as “*a potential risk for the user or influences/disturbs or interrupts the function of the structure, one that may require repair or replacement now and in the future, one that may imply subsequent damage, one where monitoring is recommended due to the uncertainty of the type, cause and development rate of damage*” (fib CEB FIP, 2002). The details and methods for inspections of concrete structures can be consulted in guidelines (CUR report 172, 1994b; CUR recommendation 72, 2011).

If technical surveys are carried out for concrete conservation (in practice, they are not always carried out), very often the people (expertise) and the methodologies applied are the same as for ordinary concrete inspection. As these experts are not trained for conservation, it is understandable that the supposed research questions for the technical investigation are the same and mainly concern the function and safety of a structure.

In principle, damage assessment of historic concrete does not differ from the assessment of other concrete structures. Some details might require extra attentions, such as additional calibrations of instruments during inspection as type and location of the reinforcement might differ. The use of non-destructive methods instead of destructive methods should be considered to avoid damage on the historic material. The degradation mechanisms for modern and historic concrete are the same, yet historic concrete can be more prone to some degradation mechanisms than modern concrete (see Part I *Understanding and Characterisation of Historic Concrete*). For the evaluation of both damage and cause of damage, it has to be kept in mind that the properties of the historic concrete can differ from modern concrete and experience is required when it comes to identifying and interpreting historic concrete and cause of damage.

Consulting construction historical reports during the technical investigation is advisable for several reasons. They can give additional information on the expected properties of the historic concrete and possible external events (for example floods, battles, fires, modifications). Detailed construction historical reports can give indications on the constituents used, construction methods and on possible causes of damage which are less common or less severe for modern concrete. The historic background may give information on unusual or deviant designs and possibly resulting poorer performance. Therefore, a more thorough investigation of the state of conservation and material properties of historic concrete might be required, regardless whether repair or conservation is planned. The planning of a technical investigation can be optimised; possibly vulnerable locations or elements with deviating properties can be identified and suitable sampling and testing locations chosen, where the impact on the historic material and heritage values is less.

For conservation, the research questions for technical surveys have to be modified. Besides safety and functionality of the structure, the safety of the heritage values should be investigated. In addition, the possibly different properties of historic concrete should be determined which influence the choice and suitability of possible repair techniques (see Chapter 9 *Impact of repairs on historic concrete and heritage values*).

To decide whether and when an intervention is necessary, a prediction of the progression of damage and the risk of attaining a critical state is required, not only to guarantee safety and functionality, but also to limit the loss of original material as interventions can be limited to the required minimum. Probabilistic models are available to predict the propagation of corrosion induced by either chloride or carbonation (DuraCrete R17, 2000; The European Union - Brite Euram III, 1998, 1999). Though usually applied to civil engineering structures, their use should be considered for historic concrete structures (see for example Müller, 2010).

In addition, a not uncommon problem are (official) statements regarding the state of conservation by non-experts without a background in either materials or repair; not only for historic concrete but for other material classes encountered during conservation as well. It is unfortunately rather common that incorrect

statements concerning the state of conservation, damage diagnosis and even repair advices are given during architectural or construction historical-surveys, either orally or written, and later used during conservation. However, they are not based on material research to identify the damage, but based on empirical knowledge and hearsay. Such damage diagnoses and suggestions for repair given by historians in a historical survey can be very detailed (see for example Beek & Kooiman Cultuurhistorie and Bureau M&DM, 2007). A high risk lies in such an advice as it can cause a false sense of security since it will be understood as an expert advice by laymen and maybe even by restoration architects. If during the conservation planning process, either by the restoration architect or by the heritage care institutes, the uselessness and even wrongness of such statements are not recognised, the conservation of the concrete is jeopardised. In addition, if the cause of damage is not correctly identified, possible safety risks might be overlooked, or costs unnecessary increased as incompatible, or less durable interventions chosen.

A prerequisite of successful conservation, like any interdisciplinary action, is the awareness of one's own expertise and the understanding when it is necessary to consult other experts. Even for concrete repair experts, the investigation and repair of historic concrete can be challenging, as its properties might be different from modern concrete, influencing the degree and possibility of certain damage types. The goal of the different investigations, technical or historical, and their expertise and differences have to be understood by all parties involved.

8.4.2 How to relate heritage values and the state of conservation

For conservation it is not sufficient only to investigate threats to the structure but also threats to the heritage values have to be investigated. Whereas threats to historic concrete as a material can be identified by common assessment techniques and by enlarging the knowledge of historic concrete, an evaluation of the threats to the heritage values of historic concrete requires a different approach. To analyse these, it is necessary not only to know in which way the heritage values are related to the material and construction method (see Section 8.3), but also to correlate heritage values with identified degradation mechanisms and their symptoms.

Understanding the mutual relationship can give twofold information: it can indicate heritage values at risk, but it can also identify whether the origin of the heritage values and the cause of damage is the same, a constellation which can cause dilemmas when it comes to choosing a conservation strategy; this will be discussed in Part III of this thesis.

In order to evaluate the impact of the state of conservation on the heritage values it is necessary to investigate and report the encountered damages more holistically, meaning the impact on either the structural integrity and on the material. This should also be done for normal concrete structures, but for conservation it is even more crucial. Besides mentioning causes of damage and mapping of damage, possible and present damage symptoms should be described, and mentioned

Table 8.3 Overview of different degradation symptoms/alterations in relationship with the location.

Surface	Bulk	Reinforcement
• Material loss (e.g. spalling, scaling) • Cracking • Deposits (e.g. soiling, efflorescence, rust stains, soot) • Graffiti • Coverings (e.g. paint, coatings, cladding) • Colour alterations (e.g. fading, erosion of cement film, mismatching repairs, local cleaning) • Textural changes	• Material loss • Disintegration • Cracking • Delamination • Dissolution • Chemical alterations (e.g. carbonation, oxidation, hydration) • Formation of new compounds (e.g. ettringite, ASR-gel)	• Material loss • Alteration of the reinforcement system • Loss of texture • Loss of geometry • Loss of connection

which material aspects will be affected. The degree of risk towards heritage values and historic concrete does not have to be identical. Different combinations are possible: both heritage values and the material are endangered; only the material is endangered but not the heritage values, or the heritage values are but not the material. The investigation should therefore explicitly consider threats towards the heritage values, as their endangerment should require action as well.

When the mutual relationship between heritage values and the historic concrete is known (see Section 8.3), it can then be reviewed whether the encountered damage and damage symptoms are related to the heritage values. In Table 8.3, an overview is given of different degradation symptoms/alterations which either affect the surface, the bulk or the reinforcement of the concrete. For example, most degradation symptoms affect the surface of the concrete, due to cracking, spalling, staining or leaching (see Figures 8.7 to 8.11). Therefore, any damage mechanism leading to these symptoms is a potential threat to heritage values related to the surface. Yet not only can the surface be affected but also the concrete bulk (e.g. aggregates, binder, original mix design) or the reinforcement (Figure 8.9).

A universal answer to which heritage values of historic concrete are at risk cannot be given due to the varieties of heritage values and diverging properties of historic concrete. To be able to identify the risk towards the heritage values, it is necessary to understand what the effects of the different degradation mechanisms are on the historic concrete and its appearance. This includes alterations and losses as well as deposits on or in the historic concrete, comprised by its surface, body and reinforcement, if any.

A different but related aspect is the mutual relationship of the cause of damage with heritage values. In Table 8.2, an overview is given of aspects of the historical

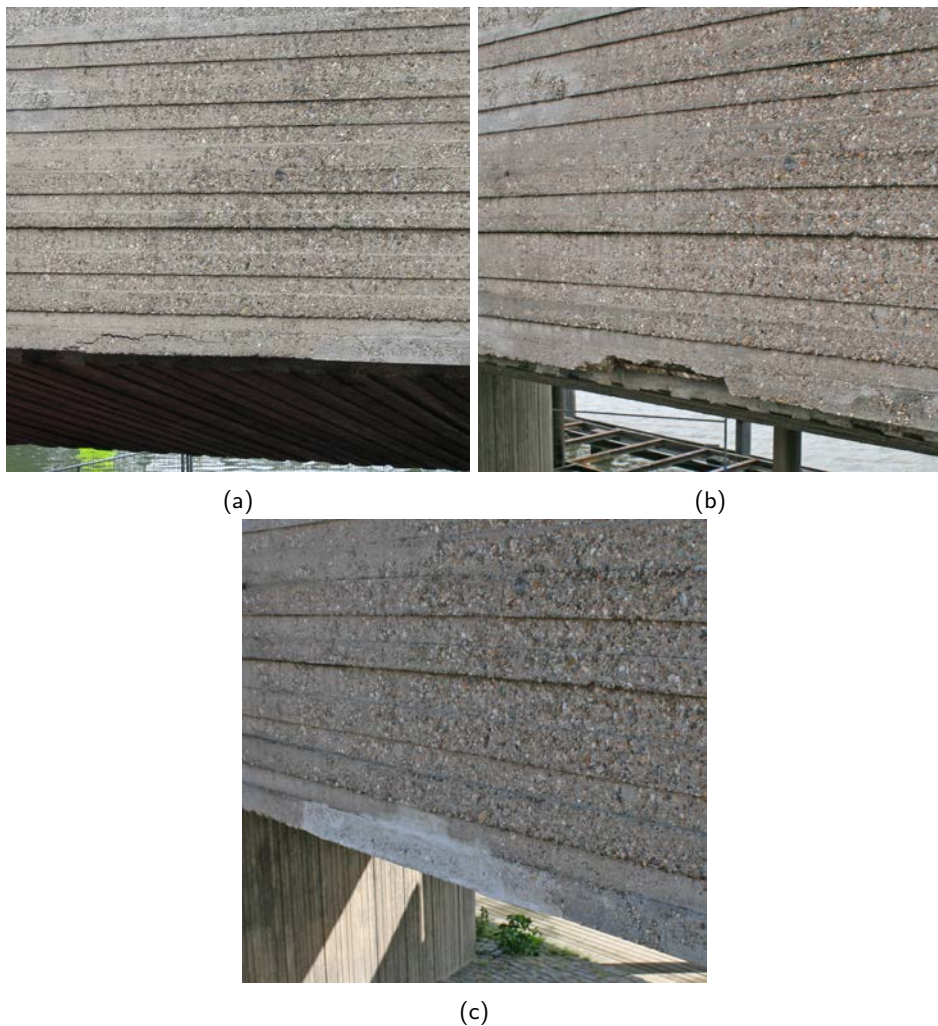


Figure 8.7 Example of the increasing impact of corrosion on an exposed concrete surface. a) Crack at corner wall / soffit (situation 2006). b) Spalled corner (situation 2007). c) After local patch repair (situation 2010) (Pumping station Parksluizen, Rotterdam; G. J. van der Grinten, 1967).



Figure 8.8 Biological growth on concrete surface, spalled concrete and corrosion (casement V, Defence line Kornwerderzand, 1933, situation 2009).



Figure 8.9 Loss of entire cross section of a reinforcement bar and parts of the concrete bulk (Dresselhuys pavilion, Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928, situation 2008).



Figure 8.10 Deposits caused by leaching and cracking (Fort near Hoofddorp, 1904, situation 2006).



Figure 8.11 Damage caused by impact of shells during the Second World War (kanonkazemat VI, 1932, Defence line Kornwerderzand, situation 2009).

context which could have influenced the design and material choice. In Part I of this thesis, it has been seen that the concepts of durability changed over time, driven by scientific and empirical insight. Specific properties originating from the construction period can have led to degradation. A common example is a concrete cover depth which is considered now as too little, resulting in corrosion and spalling (see for example Figure 8.7). If these buildings would be designed nowadays, they might have different proportions. A different aspect is related to former state-of-the-art, where supposedly high quality mix design and construction led to deterioration later on (Figure 8.10). Less common are heritage values related to historic events, such a historic warfare causing damage (Figure 8.11). Whereas one interpretation of damage is as a threat towards heritage values, a different interpretation of damage is as an expression of the heritage values.

Evaluating concrete within the historical context and comparison with buildings from the same period, and possibly with objects made by the same company can indicate whether the quality of the concrete is not only poor compared to present standards but was already below average at the time of construction. For example, the design of circumambulation passageway of the Pilgrimage church in Brielle (1912) is based on a previously burnt down timber construction, reconstructing its shape in reinforced concrete (Monumenten Advies Bureau, Haans, Delmee & van Hest, 2010a,b). As the dimensions and details of a timber structure were not optimised for a reinforced concrete structure, locally high concentrations of reinforcement can be found, preventing adequate compaction of the concrete. Many concrete elements now show detachment of the concrete cover (see Figure 8.12 and 6.37a). Different buildings from the same period, even those executed by the same company, show that a better concrete quality was possible then (for example the former *Hotel Twee Steden* in The Hague, Figures 7.2 and 7.24).

When working with historic objects, the anticipated signs of ageing or patina are often accepted; however, to define whether the encountered patina disturbs or enhances the heritage values requires a critical interpretation (Philippot, 1996). Similarly, care is required when interpreting the state of conservation and its relationship to the heritage values. Listed buildings are not museum objects and should have a function; therefore, a careful balance between safety and preservation of values has to be assured.

Deterioration does not automatically pose a threat to values related to the original material. Although the historic concrete might show deterioration, it can still be in a sufficiently sound condition to transmit the ascribed heritage value on-site, provided it can be demonstrated that future development of damage is sufficiently slow. Such cases show that a profound evaluation of any damage and its progress is necessary to determine the safety of both heritage values and structure.

To illustrate different constellations of heritage values and state of conservation, three Dutch examples will be investigated in more detail in the following sections. The mutual relationship between the development of concrete technology, building typology and interpretation of related degradation will be shown



(a)



(b)



(c)

Figure 8.12 Example of an early reinforced concrete structure based on a timber design and relating degradation due to the geometry of the design and quantity of reinforcement (circumambulation passageway of the Pilgrimage church in Brielle, H. Goossens (reconstruction), E.J. Margy, 1912 situation 2010). a) Overview of passage way. b) Detail of a corner at the intersection between two rafters and column. c) Exposed reinforcement after hydrodemolition, showing a high concentration of reinforcement bars.

by means of Fort Bezuiden Spaarndam, a plain concrete structure built between 1897-1901. A similar situation can be envisaged for the Hofplein railway viaduct (1900-1908), presenting the development of reinforced concrete and appearance of concrete structures. In addition, this structure underwent several changes. Finally, the enhancement of heritage values through ageing and the identification of historic events will be illustrated by the earth retaining walls of the unfinished Groot Museum (1921), once intended as an architectural icon.

8.5 Fort Bezuiden Spaarndam (1897-1901)

The Stelling van Amsterdam (1883-1920) has been mentioned in Part I *Understanding and Characterisation of Historic Concrete* to illustrate the pioneering work of the Dutch military regarding plain concrete structures.

Fort Bezuiden Spaarndam (1897-1901, Figure 8.13 and Figure 8.14, see also Section 1.3.2), a plain concrete structure, is one of the earlier concrete forts of the Stelling van Amsterdam (Heinemann et al., 2008, 2011). The Stelling van Amsterdam was inscribed in 1996 as a UNESCO World Heritage Site, amongst other aspects, for its significance in the development of concrete technology. It is evaluated as “*an outstanding example of a type of building, architectural or technological ensemble [...] which illustrates (a) significant stage(s) in human history*”. The justification was that “*in the Europe of the 19th century, the Stelling van Amsterdam was considered a leading example of a ring of forts. [...] The forts illustrate the transition in building and architecture from brick construction in the 19th century to applying reinforced concrete in the 20th century. This transition especially, with its experiments in concrete and emphasis on applying unreinforced concrete, is an episode in the European history of architecture which in the material sense has only rarely been preserved*” (UNESCO, sa). It is considered authentic in material and substance as “*the works were built with exceptional care. They have been preserved as they were designed and specified. The materials and building constructions used have also remained unchanged. Repair in arrears applies in some cases. No parts of the Stelling have been reconstructed.*”(i); Each individual and combined part of the structure of the Stelling van Amsterdam is a significant social, cultural-historical and scientific source of historic material [...] Its outstanding universal value is expressed in the authenticity of the design (the typology of forts, sluices, batteries, line ramparts), of the specific use of building materials (brick, unreinforced concrete, reinforced concrete), of the workmanship (meticulous construction apparent in its constructional condition and flawlessness), and of the structure in its setting [...]” (UNESCO, sa).

From the above description, it can be deduced that, in this case, the original historic concrete is of high value and should be preserved. More detailed questions arise about the way the historic concrete of the Fort Bezuiden Spaarndam contributes to the documentation of the technological development of concrete in

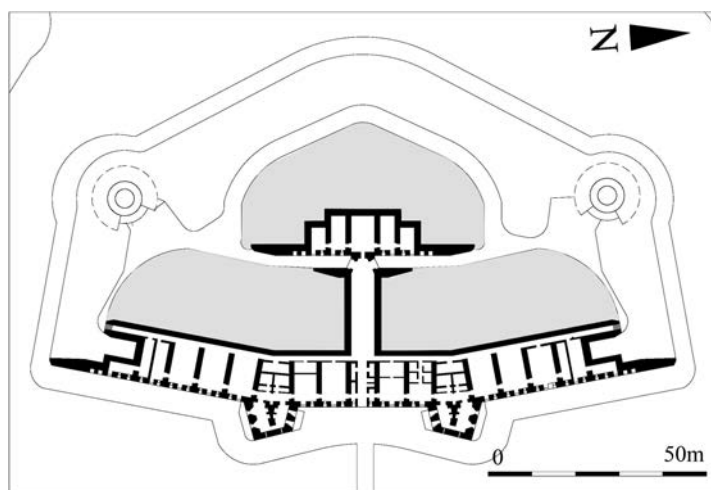


Figure 8.13 Site plan Fort Bezuiden Spaarndam.

the Netherlands, not only for military buildings but concrete buildings in general.¹ The question is which material aspects are characteristic for early plain concrete military structures and how it relates to concrete technology of the specific period. From the importance of the structure and its defence function, the concrete may be supposed to be of high quality for its time.

The historical context concerning concrete technology was one without any codes of practice; most knowledge was empirical and theories for good concrete differed from modern concepts (for example with respect to aggregate grading and durability). Military engineers carried out tests to evaluate the strength of plain and reinforced concrete against the impact of shells. The influence of military engineers, especially Scharroo and Van Hemert, reached further than only military structures, as they greatly helped to disseminate knowledge of concrete technology and construction on a wider scale (see Section 2.2 *Historical context*).

A development of material use can be observed within the defence line. In the middle and late 19th century, lime and trass-based binders were used and later replaced by more expensive but stronger Portland cement. Crushed stone as aggregate was preferred over gravel as its rough surface and sharp edges allowed in theory a better bond between aggregate and cement, even though it required a higher cement and water content, and thus was even more expensive.

This led to the choice of strong but expensive concrete with Portland cement and crushed stone (porphyry from Quenast, Belgium) for the important exposed elements such as the casemates and exterior walls (see Figures 4.3 and 4.7). For secondary elements, such as interior walls, locally available gravel was used as aggregate, for minor elements broken bricks. A characteristic of the construc-

¹For the case study in this thesis, the state of conservation of the fort before the 1990s intervention will be used, i.e. without crack repairs, new expansion joints and no cleaning of the façade.



Figure 8.14 Overview gorge façade Fort Bezuiden Spaarndam (1897-1901, situation 2006).



Figure 8.15 Interior of Fort Bezuiden Spaarndam with visible wooden boards cast into the concrete wall for the later attachment of interior elements (situation 2006).

tion period is the coarseness of the Portland cement, indicating earlier production methods (see microphotograph in Figure 3.15). The original military function is reflected in the chosen constituents as for civil structure usually cheaper gravel was used (compare also with the following case in Section 8.6). Comparing the concrete mix of Fort Bezuiden Spaarndam with earlier forts, one can notice that previous concrete was sometimes made with a trass-Portland cement or trass-lime cement in combination with broken bricks as coarse aggregate, so-called *brikkenbeton*. Later forts were usually made with Portland cement and gravel (see Chapter 5 *Concrete mix design*). The understanding of the benefits of reinforced concrete led to design changes and later forts were reinforced (see Section 6.2 *Application and history of reinforced concrete*).

The typology of the forts changed with the introduction of concrete. Fort Bezuiden Spaarndam was designed as a plain concrete structure conform the so-called standard model A, which distinguishes itself from the earlier brick masonry forts (Vesters, 2003). The design is optimised to give protection against the impact of shells and balancing construction costs. Small details indicate the construction period. In the interior, wooden boards were cast into the wall for the later attachment of elements as concrete was too hard to nail in (see Figure 8.15). The limited understanding of the thermal behaviour of plain concrete is reflected by the absence of expansion joints in the design, despite the length of over 100 m of the rear façade. Consequently, cracks developed in the plain concrete to compensate thermal stresses (see Figure 1.8).

In the context of the defence line and the construction period, the specific concrete mix design and the fact that the concrete is not reinforced are relevant representatives of the heritage values, which is even enhanced as evidence and variations of plain concretes from this period are rare in such a large context.

The original appearance of the fort is not documented. Local remains of a former green paint are visible, which could have been early camouflage paint (Figure 1.7). Lime washes and thin layers of cement based washes were common for early concrete military buildings (Minister van Oorlog, 1906). As the military function of the fort ceased in 1960, it is questionable whether the painting would have been renewed since then. With the façade cleaning in the 1990s, some paint would have been removed. What can still be seen are the remains of a thin cement wash on the surface (see Figures 1.7, 7.21 and 7.27).

Nowadays, the important parts made with porphyry show signs of Alkali-Silica reaction (ASR) due to the combination of used raw materials. When analysing the state of conservation together with the material aspects attributed to the heritage values, dilemmas suddenly become obvious as in this case the heritage values and degradation have the same material origin. The former intention to use a very high quality concrete for the crucial concrete members is one of the main causes for the presence of damage today. There are two options for interpretation of the present damage: it is the direct result of misconceptions of former concrete technology from an experimental phase and hence the damage acceptable; or, despite the fact that the original concrete mix is the cause of damage, the ASR is a threat to the

original material, either in form of still on-going reaction (if tests confirm it) or through secondary damage caused by the cracks.

8.6 Hofplein railway viaduct (1900-1908)

The historic concrete of the Hofplein railway viaduct in Rotterdam (1900-1908, Figure 8.16) reflects many heritage values related to scientific significance and early reinforced concrete technology in the Netherlands. In Part I *Understanding and Characterisation of Historic Concrete*, the viaduct has been mentioned several times for its role in the development of reinforced concrete theories and concrete industry in the Netherlands. Especially, the diversity and evolution of the reinforcement are noticeable and the reaching of independency of proprietary reinforcement systems (see Section 6.2 *Application and history of reinforced concrete*). The surface finish of the concrete with a *kunstzandsteenpleister* (“artificial sandstone render”) and tooling represents the construction period and typology very well (Figures 7.25 and 7.26).

The Hofplein railway viaduct was listed as a *Rijksmonument* (the highest Dutch category of listings) in 2002, as it was built for the first electrical railway in the Netherlands and its innovative building technology, with additional architectural, cultural-historical and urbanistic values (RCE, 2002a). Additionally, with nearly 2 km of length, it was the largest reinforced concrete structure in the Netherlands at the time.

With the planned transformation of the viaduct after the ceasing of the railway function, the history of the viaduct has been studied by architectural and urban historians (Crimson Architectural Historians, 2007, 2008; Steenhuis stedenbouw/landschap and DaF architecten, 2005). In these reports, mainly the architectural or urban history of the viaduct was investigated. However, statements regarding the construction history were made, especially regarding the used reinforcement system and surface finish; the construction history was not studied in detail and some details were misunderstood, especially regarding the rigid reinforcement systems and applied surface finish.

Reviewing the construction history of the viaduct, its innovative building technology is confirmed. No code of practice for reinforced concrete did exist yet; the dissemination of knowledge to design and construct reinforced concrete was in its infancy. The Hofplein railway viaduct represents a turning point from the dependence on patent systems (such as the initially intended Hennebique system) to freely available knowledge of calculation, design and application by engineers. The innovativeness in methods of calculation, in material testing to obtain realistic values for calculations and attempts to design a durable concrete structure has been documented by the designing engineer Van Hemert (1901, 1908). Van Hemert's research was fundamental, as he tried to understand the properties of concrete relevant for a structural design under real-life conditions and not laboratory conditions. Van Hemert based his testing on the experiments of the French



(a)



(b)



(c)

Figure 8.16 Three different construction phases of the Hofplein railway viaduct (situation 2010) a) Emplacement with vault structure and use of round reinforcement bar (1904). b) Use of a rigid reinforcement system made from profiles (1904); clearly visible are the additions from the 1950s with columns and extension of the width. c) Last phase finished in 1908 and made with round, plain reinforcement bars.

Considère (see for example Sanders, 1907), however Van Hemert disagreed with the type of samples Considère used, which were without coarse aggregates. Van Hemert judged that such samples and the obtained results would not reflect the concrete used in Dutch practice in terms of both dimensions and material composition. Therefore, Van Hemert used samples reflecting the concrete and materials (coarse and fine aggregates, cement) available in the Netherlands (Van Hemert, 1901). The materials and mix design for the construction of the Hofplein railway viaduct were specially chosen based on the experiments used to obtain the material parameters for calculation. The criterion for the material choice for the reinforcement (*vloeiijzer*, ingot iron) and the concrete mix design were to balance costs, construction methods and performance. Additionally, Van Hemert considered the thermal behaviour of the reinforced concrete and tried to design the viaduct with sufficient abutments to compensate the stresses.

The technological evolution can be seen in the different reinforcement systems applied, from a reinforcement system using round bars and strips for the vaults at the emplacement (Figures 6.20 and 8.17), via a less common rigid reinforcement system using profiles for the first built part of the viaduct (Figures 6.22 and 8.18), to a then more common reinforcement system with round bars for the last phases. The rigid reinforcement system is most likely not a pure Melan system as stated in existing reports (Crimson Architectural Historians, 2007, 2008; Steenhuis stedenbouw/landschap and DaF architecten, 2005), as it was neither carried out under the license of Melan, nor calculated according to the design theories developed by Melan. It is more likely that Van Hemert was informed about the different existing rigid reinforcement systems and underlying theories, as far as they were available, and performed his own design and calculation.

The surface finish of the concrete is representative for the construction period for infrastructure in an urban environment. The use of ground sandstone to modify the colour of the render corresponds with the period (see Section 7.5.2 *Coloured aggregates*), as does the imitation of natural stone tooling in the render. Historic events such as the fire during the bombardment of Rotterdam in the Second World War in May 1940 can be seen in the discoloration of the aggregates in both concrete (see Figure 4.16) and render (see Figure 7.26) of the vaults of the emplacement. The border of the fire can be traced back in the monument and corresponds with a light installation in memory of the fire (Figure 8.19). During the last century, the viaduct underwent several changes, either to adapt the function, improve the design or alter the appearance. Especially the appearance has been altered by painting the surface white (and other colours) and by local repairs without adapting to the texture or colour to the original surface (Figures 8.20 and 8.21).

Concluding, the heritage values relate mainly to the different reinforcement systems used and their respective geometry, connection, design, material choice and appearance; aspects that are in most cases not visible. The original surface appearance is directly related to the composition of the render, which was made with ground sandstone and a lime-Portland cement render, and to the applied texture. The original concrete supports the historic information of the underlying



Figure 8.17 Example of local damage of render and concrete, exposing the reinforcement, in this case round bars and round stirrups (Hofplein railway viaduct, situation 2009).



Figure 8.18 Example of an arch without the original surface. Instead a smooth, grey render was applied and painted white. The original reinforcement is visible due to local damage, notice the rectangular strips and horizontal plain round bars (Hofplein railway viaduct 1900-1908, situation 2012, compare also Figure 6.22).



Figure 8.19 Location of the *brandgrens* (fire border) of the fire May, 1940 during the Second World War (Hofplein railway viaduct 1900-1908, situation 2012). The arrow indicates a lamp in the ground, which is part of a memorial, outlining the *brandgrens*. The render is discoloured in this area due to the fire, locally visible under the paint. Notice the biological growth caused by seepage through the roof.



Figure 8.20 Example of different interventions and resulting surface finish: the soffit shows a grey concrete from 1950s extension, next to it an original reddish stripe of render with locally exposed reinforcement and the white painted intrados with local repairs without texture (Hofplein railway viaduct 1900-1908, situation 2012).

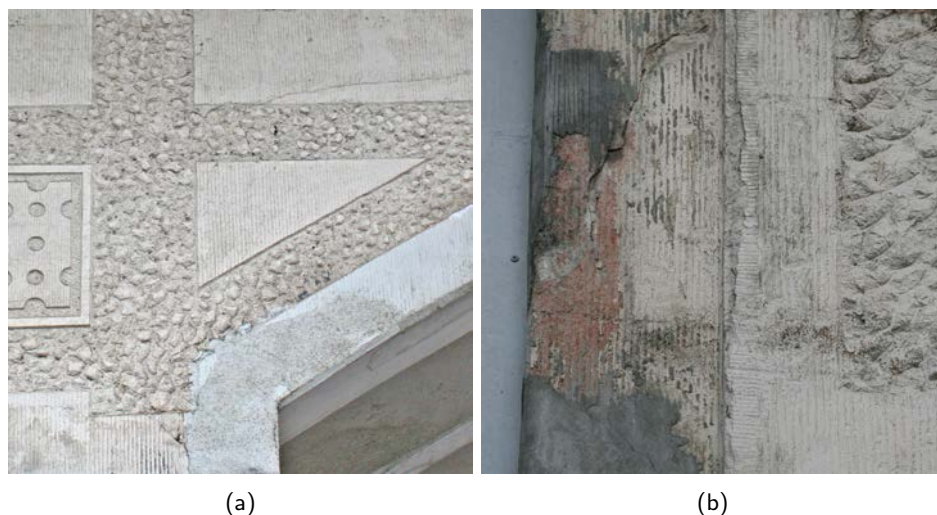


Figure 8.21 Two examples of mismatching previous repairs, affecting the appearance of the surface (Hofplein railway viaduct 1900-1908). a) White painted local patch repair without textural adaptation (situation 2009). b) Colour and textural alterations due to local grey repairs, white painting and soiling, the original reddish render colour is locally visible (situation 2009).



Figure 8.22 Application of sprayed concrete in the vaults of the emplacement, this technique was chosen due to the size of the intervention and the costs (Hofplein railway viaduct 1900-1908, situation 2009).

conscious choice of materials (Portland cement and gravel), mix design (cement content, limited aggregate size) and evidence of the fire in 1940. In terms of threats it is mainly the surface which is threatened, as it has been altered with interventions, whereas the original reinforcement is still present, although it is locally threatened and even destroyed due to corrosion. The bulk and surface are locally endangered by on-going degradation (cracking, seepage, see Figures 8.18 and 8.19). The desired high durability of the reinforced concrete has not been achieved and early on repairs have been carried out. Some repairs reduce the aesthetical values of the surface (Figures 8.18 to 8.21). Locally, original concrete in the emplacement has been removed in 2009 and replaced with a layer of sprayed concrete (Figure 8.22).

8.7 Earth retaining walls of the unfinished Groot Museum (1921)

The earth retaining walls, made from reinforced concrete, and some dispersed blocks of Maulbronn sandstone, once intended to clad the walls, are the only existing remains on-site of the Groot Museum for the art collectors Kröller - Müller in the national park Hoge Veluwe, designed by H. van de Velde (1863 - 1957, see Figures 8.23 to 8.27). The construction of the museum started June 20, 1921; works ceased May 7, 1922 due to price inflation. Van de Velde continued designing the museum until 1929, but the museum was never finished. Instead, a smaller museum was built nearby in the national park (Sembach, Schulte & Breuer, 1992). The earth retaining walls were left unfinished and traces of the workmanship can still be encountered unaltered on-site (Figures 8.26 to 8.28).

At that time, reinforced concrete had become a common construction material for structural elements (see Section 2.2.3 *Interwar period: standardisation and professionalisation*); cladding of concrete with natural stone was not uncommon for large representative buildings (see Section 7.2 *The development of concrete surface finishes*). Concerning construction and knowledge dissemination, concrete technology was in a transition from empirical to a scientifically supported general application. The G.B.V. 1918 was applicable.

The earth retaining walls, which are listed as a monument, are considered of value as a tangible artifact for the once intended Groot Museum and as part of the development of the national museum park (Gemeente Ede, 2007). Besides being the only remaining built evidence of the Groot Museum, the retaining walls document the ceasing of the works and give insight into concrete technology and construction of the early 1920s. After the work had been ceased, the walls were left uncovered and no intervention has been carried out since; traces of workmanship can still be observed. In Figures 8.28a and 8.29a, remains of the timber formwork are still visible, and due to the protected location, textural details of the timber formwork can still be seen. Such traces of workmanship are usually not visible



Figure 8.23 Overview of the earth retaining walls of the sculpture yard (Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008).



Figure 8.24 Overview of the walls of the terrace, which were initially intend to be earth retaining (Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008).

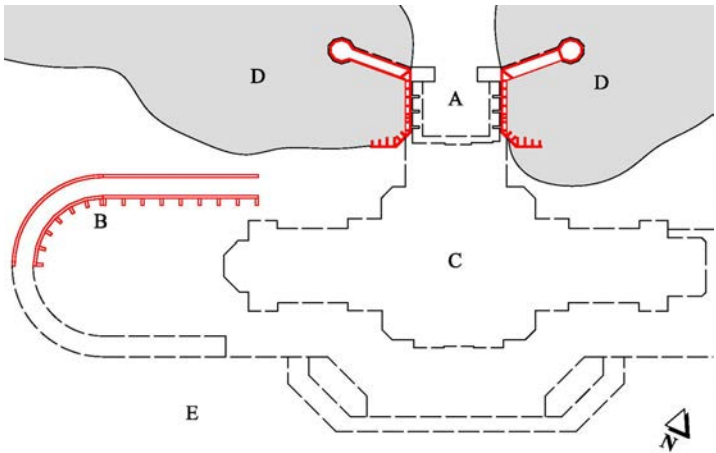


Figure 8.25 Overview of the site with the investigated retaining walls (red) (Drawing not to scale.) **A** Retaining walls of the sculpture yard, **B** Retaining walls of the terrace, **C** Outlines of the planned Groot Museum, **D** Hill, *Franse Berg*, **E** Plane, *Pampelse zand* (Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008).



Figure 8.26 Examples of dispersed blocks of Maulbronn sandstone spread near the walls of the terrace (Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008).



(a)



(b)

Figure 8.27 Details of the construction to place the natural stone blocks (Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008). a) Hook cast in the concrete to place a block. b) Rear side of a block showing the opening to insert the hook.

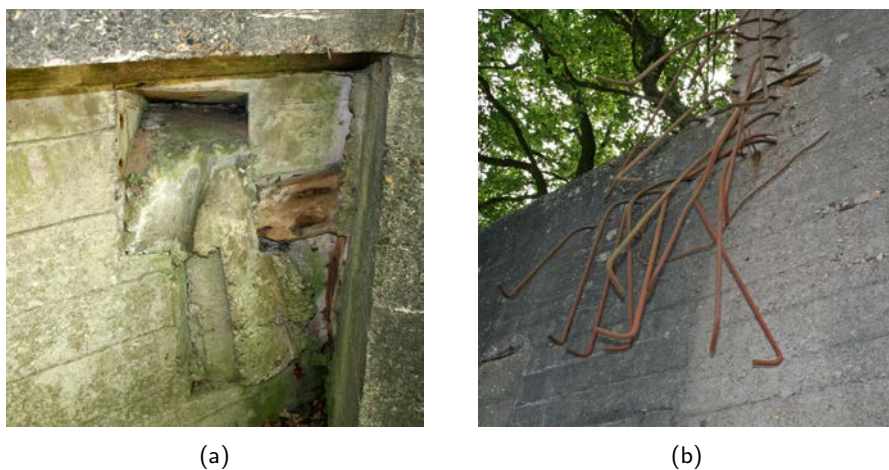


Figure 8.28 Evidence of the sudden cease of the construction works (Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008). a) Remains of the wooden formwork and still visible texture caused by timber formwork. b) Visible starter bars indicating the intended continuation of the wall.



Figure 8.29 Signs of merging with the landscape and local degradation (Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008). a) Colour variation of the concrete caused by biological growth, and local spalling of the concrete; notice the remains of the original formwork in the corner. b) Colour variation of the concrete caused by biological growth.

anymore at other historic concrete structures, as they are either covered with renders or former interventions already have removed or obscured them. Therefore, these traces are not only important for this specific monument but also for Dutch concrete heritage and concrete history in general. Locally, exposed starter bars (Figure 8.28b) indicate that the works were ceased and that the intended size of the structure was larger.

The historic concrete shows signs of degradation, such as spalling, probably caused by a too thin concrete cover and subsequent carbonation induced corrosion (Figures 8.29a, 6.12, 6.38a). In many places, the concrete is covered with biological growth and the texture of the timber formwork imprints have disappeared (Figure 8.29b). Locally, erosion has exposed the aggregates (Figure 4.17). Historic material is slowly lost due to corrosion and erosion, but as the walls have no function the demands towards their safety is reduced. The biological growth reflects the setting in a national park and the merging of the walls in the landscape (Heinemann, 2008a).

The fact that no maintenance or repair have been carried out, and that degradation took place slowly, underlines the ruin atmosphere of the site. Therefore, the loss of historic material is in this case not a threat towards the heritage values, as the cause of material loss - ceasing of the works, abandoning of the site - is part of the history of the monument. The several remains reflecting previous concrete technology and construction add to the history of the monument and allow the study of former workmanship. These characteristics and the merging of the walls during nearly a century with the landscape of the national park, represent the heritage values ascribed to the monument.

8.8 Conclusions

In this chapter, it was shown that it is necessary and possible to correlate the heritage values with the historic material and its degradation. Without determining the mutual relationship it is not possible to identify and discuss possible threats towards the heritage values. This includes not only the original state of the concrete, but also its present condition and historic events in the building's lifetime. In this context, possible alterations and degradation symptoms should be reviewed for the relation with the heritage values, as they can either be a threat, indifferent or even an enhancement of the heritage values.

With this insight, it is possible to outline the necessity and the boundary conditions for interventions which integrate both technical demands and the preservation of the heritage values and will be discussed in Part III. However, before discussing potential conservation aims it is necessary to understand what the impact of different repair techniques can be on the historic material and on the heritage values, which will be done in the following chapter.

Chapter 9

Impact of repairs on historic concrete and heritage values

Chapter Outline

In the previous Chapter 8, the mutual relationship between heritage values, the historic concrete and the state of conservation was discussed. Indications were given whether, at the present state of conservation, the heritage values or the historic concrete were at risk, and therefore an intervention could be initiated. In this chapter, different repair techniques will be reviewed from a concrete conservation point of view. This includes a discussion of the differences between concrete repair and concrete conservation, and the resulting differences in aims and demands towards repair techniques. In addition, the deviating properties of historic concrete can influence the effectiveness of a treatment. The preservation of heritage values can furthermore require a modification of common approaches.

9.1 Introduction

Sooner or later during their service life, concrete structures require repairs to treat damage. Repairs are carried out to restore the structural health, the functionality or the appearance. The properties of the concrete influence not only degradation but also the choice of repair techniques. Background information on the construction history (see Part I *Understanding and Characterisation of Historic Concrete*) is therefore not only relevant in order to understand the construction history of a building but also of utmost importance for technical aspects such as surveys and choice of appropriate repair techniques. It can help to better understand present damages as it explains deviations from modern practice in design and composition which influence the properties of the concrete. When it comes to repair, mater-

ial properties and cause of damage determine the technical framework of possible interventions.

It is not the aim of this chapter to discuss the details of existing repair techniques, as for this matter several publications exist and can be consulted.¹ Additionally, the field of concrete repair is constantly developing, which might lead to new developments or more sophisticated models and materials applicable for concrete conservation. Instead, this chapter will give an overview of existing repair techniques and their (theoretical) potential for conservation. This includes their possible positive and negative impact on the historic material and heritage values, as well as indications of critical properties of both the historic concrete and the repair material which could challenge their use for historic concrete.

Current obstacles in the process of conservation of historic concrete are not only the lack of information on these aspects but also the fact that they are often not considered when planning an intervention. Additionally, communication barriers exist between the executing and planning concrete repair experts, and the planning and deciding conservation stakeholders as they are not familiar with each other's topic, yet depend on each other. To overcome these obstacles, knowledge exchange on both groups' backgrounds is necessary as well as the explanation of the terminology they use, to enable them to communicate. This includes the capability (for restoration architects etc.) to evaluate suggested repair approaches. This requires an understanding of the principles of repair techniques and whether a suggested technique (or none at all) will treat the cause of damage and/or its symptoms, its impact on the building, the historic concrete and heritage values, and the durability of the intervention, and the consequences of multiple intervention cycles.

Before discussing the impact of concrete repair techniques on the historic concrete and possibilities of modification, it should be explained why standard concrete repair techniques are usually neither designed nor evaluated for their use in a conservation context. Therefore, the differences between concrete repair and concrete conservation will be discussed in Section 9.2. Although closely related, the two fields of concrete repair and concrete conservation have diverging aims, criteria and even terminology. Their background and aims will be explained to clarify why existing repair techniques have to be reviewed for their suitability for conservation. This includes indications of retreatability and durability, aspects which are relevant when considering the increased service life which is desired for heritage structures, compared to normal structures.

Additionally, heritage care authorities exclude or mistrust some techniques based on previous bad experience, although they could be beneficial in some cases, depending on the cause of damage, the material properties, and the heritage values to preserve. To encourage a prejudice and dogma free discussion of which techniques are suitable for a conservation project, information is missing on the

¹For example: ACI & ICRI, (2007a; 2007b); ACI Committee 546 (2006); Bertolini, Elsener, Pedferri & Polder (2004); Broomfield (2003); CUR (1994b; 1997a; 1997b; 1997c; 1997d); fib CEB FIP (2002); Grantham (2011a); ICRI (1996); NEN-EN 1504-09:2008 and Woodson (2009).

impact of an intervention on the heritage values and on the historic fabric, and the influencing properties of historic concrete when it comes to the feasibility of certain techniques.

This chapter neither replaces detailed investigations and material research nor gives solutions on which approach would be the most suitable for a specific case. Such decisions have to be made case specific for each historic concrete building by specialists and include many aspects such as the underlying cause of damage, the material properties, the heritage values to preserve, the treatment of cause of damage or symptoms, structural aspects, exposure conditions and conservation aim.

9.2 Conservation or repair?

Due to the similarities between concrete repair and concrete conservation in terms of material, underlying causes of damage and repair techniques, the fundamental differences between repair and conservation are not often considered in research or in practice. As damage processes are the same for historic and modern concrete, it might seem correct to apply the same repair strategies and techniques for both conservation and repair. This may result in conservation approaches which, at first sight, appear technically sound but may cause a considerable loss of heritage values. Additionally, as it was seen in Part I of this thesis, the properties of historic concrete are not always comparable to the properties of modern concrete, questioning the compatibility and usability of some repair techniques.

Other obstacles are assumptions and prejudices that concrete conservation is about retrofitting older concrete structures with a poor performance to modern standards, working with constraints such as preserving even very poor and deteriorated concrete under all circumstances, or that repairs have to be mainly “pretty”; although the latter is still too often neglected in practice. Most published case studies of repairs or interventions of historic concrete usually only discuss these challenges. Implicitly, it seems that aims and challenges of concrete conservation are either to make a repair aesthetically compatible or to improve a “poor” structural capacity. These demands can be true in some cases, but they are not the general rules nor the only options for conservation.

To understand which possible threats repair poses for a monument, one must look at the diverging aims of repair and conservation as the aims and criteria valid for concrete repair are not *a priori* valid for concrete conservation. That conservation of heritage concrete structures requires extra attention, is mentioned in several works on concrete repair, yet what the demands are in detail, and how to implement these in the repair process is not explained (see for example fib CEB FIP, 2002; Matthews, Sarkinen & Morlidge, 2007). When challenged with the conservation of a historic concrete building, it is therefore necessary to understand the differences between concrete repair and concrete conservation (Heinemann et al., 2011).

9.2.1 Repair

The aim of concrete repair can be defined as *to maintain the function of a concrete structure for a specific, often limited, period of time*. Lately, in connection with sustainability demands, there is a shift towards integrating maintenance and increasing the service life of the existing structure. Repair is usually carried out when a structure shows damage which affects its safety, function or, occasionally, the aesthetical appearance.

The criteria to choose a repair technique are described in the European standard NEN-EN 1504-09:2008 *General principles for the use of products and systems: the structural performance, the service life, economical issues and the possibilities of maintenance*. A commonly assumed service life for a concrete structure without any major repair is about 50 years, for infrastructure 100 years (Siemes, Polder & de Vries, 1998); necessary interventions are designed considering the remaining service life. The limited timeframe of a remaining service life, usually a couple of years or decades, can be a realistic goal achievable with standard repair strategies.

As intervention options, six actions are considered, with the aim to improve or restore mechanical, chemical or physical properties: *“Do nothing for a certain time but monitor; Re-analyse the structural capacity, possibly leading to downgrading the function; Prevent or reduce future deterioration; Strengthen or repair and protect all or part of the concrete structure; Reconstruct or replace all or part of the concrete structure; Demolish all or part of the concrete structure”* (NEN-EN 1504-09:2008). Depending on the underlying causes of damage, six principles of intervention are applied to treat defects in concrete and five to treat reinforcement corrosion, with each principle consisting of several methods (see Table 9.1). A repair strategy should be evaluated for whether it is *“appropriate to the type, cause or combination of causes and to the extent of the defects [...] and appropriate to the future service conditions”* (NEN-EN 1504-09:2008).

9.2.2 Conservation

Several international and national guidelines and charters discuss the aims and framework of conservation in general (for example ICOMOS, 1964; 2003a). One important goal is to preserve places of cultural significance with their history and meaning for *“present and future generations”* (Australia ICOMOS, 1999) and a main criterion for interventions should be the preservation of the ascribed heritage values of a monument (see Section 8.2 *Categories of heritage values*).

Different conservation principles exist: conservation, preservation, reconstruction and restoration. The principles differ mainly in the quantity of remaining historic material and state of conservation of the historic material and building, and the degree of intervention. The definition of the different terms is influenced by the cultural context and linguistic differences. A unified and internationally accepted interpretation and definition of the different conservation principles does not exist as it does for the principles of concrete repair.

Table 9.1 Principles and Methods for protection and repair of concrete structures (NEN-EN 1504-9:2008).

Principle	Examples of methods based on the principles
Principles and methods related to defects in concrete	
1. Protection against ingress	1.1 Hydrophobic impregnation 1.2 Impregnation 1.3 Coating 1.4 Surface bandageing of cracks 1.5 Filling of cracks 1.6 Transferring cracks into joints 1.7 Erecting external panels 1.8 Applying membranes
2. Moisture control	2.1 Hydrophobic impregnation 2.2 Impregnation 2.3 Coating 2.4 Erecting external panels 2.5 Electrochemical treatment
3. Concrete restoration	3.1 Hand-applied mortar 3.2 Recasting with concrete or mortar 3.3 Spraying concrete or mortar 3.4 Replacing elements
4. Structural strengthening	4.1 Adding or replacing embedded or external reinforcing bars 4.2 Adding reinforcement anchored in pre-formed or drilled holes 4.3 Bonding plate reinforcement 4.4 Adding mortar or concrete 4.5 Injecting cracks, voids or interstices 4.6 Filling cracks, voids or interstices 4.7 Prestressing (post tensioning)
5. Increasing physical resistance	5.1 Coating 5.2 Impregnation 5.3 Adding mortar or concrete
6. Resistance to chemicals	6.1 Coating 6.2 Impregnation 6.3 Adding mortar or concrete
Principles and methods related to reinforcement corrosion	
7. Preserving or restoring passivity	7.1 Increasing cover with additional mortar or concrete 7.2 Replacing contaminated or carbonated concrete 7.3 Electrochemical realkalisation of carbonated concrete 7.4 Realkalisation of carbonated concrete by diffusion 7.5 Electrochemical chloride extraction
8. Increasing resistivity	8.1 Hydrophobic impregnation 8.2 Impregnation 8.3 Coating
9. Cathodic control	9.1 Limiting oxygen content (at the cathode) by saturation or surface coating
10. Cathodic protection	10.1 Applying an electrical potential
11. Control of anodic areas	11.1 Active coating of the reinforcement 11.2 Barrier coating of the reinforcement 11.3 Applying corrosion inhibitors in or to the concrete

Conservation is often considered as a general term (Australia ICOMOS, 1999; Earl, 2003), and preservation, reconstruction and restoration as different degrees of interventions, using as criteria the amount of original fabric remaining on-site and the amount of newly introduced material. The main aim of preservation is considered as to retard deterioration and “*maintain [...] the fabric of a place in its existing state*” (Australia ICOMOS, 1999). During restoration, respectful interventions are carried out on existing fabric and some alterations are possible, commonly to return the monument into a known earlier state (for example Earl, 2003). In Dutch, a differentiation between conservation (*conservering*) and restoration (*restauratie*) is not explicitly made, and *restauratie* is used as a general term. During reconstruction, it is attempted to recreate a building or element, using “*historical, literary, graphic, archaeological and scientific evidence*” (Earl, 2003, p. 193), meaning that little or no historic material is present in the final situation.

In general, preservation is often considered to be the ideal option and reconstruction the least desired. In practice, differences in acceptance can be noticed, depending whether an entire building is reconstructed (Figure 9.1), which is often widely discussed, and replacement of building elements (Figure 9.2), which is less noticed in public and academia.

Acceptable repair methods for the different principles are not addressed in conservation charters, which are written on an abstract level. Deduced rules-of-thumb encountered in practice are to remove as little original material as possible, and replace like-with-like, rules which should not be supported when understanding underlying damage mechanisms and durability of repair materials. For traditional building materials such as timber more detailed principles do exist (ICOMOS, 1999).

The different concrete repair principles introduced in Table 9.1 cannot be directly translated into one of the conservation principles, although similarities can be seen (e.g. preservation and “*prevent or reduce future deterioration*”); the reason is that the main criteria for conservation, preservation of heritage values and respect for the historic fabric, are not considered in the repair principles. Understanding the differences and similarities is necessary to enhance communication and to clarify conservation aims.

Historic concrete challenges the concepts of traditional perceptions of conservation. For example, traditional structures are often assembled from smaller units, such as individual natural stone blocks or individual timber elements. A local replacement with the same type of material is (in theory) possible. Concrete, however, is an artificial product and in most cases concrete structures are monolithic, excluding local replacement without interrupting the historic concrete. Additionally, as discussed in Section 8.2 *Categories of heritage values*, the design intent of the architect is overemphasised for monuments belonging to the architectural style of the *Modern Movement*, and related conservation projects deliberately focus on the original design and partial (or even total) reconstruction and destruction of (material) historic evidence is accepted. Such tendencies are supported by lim-



Figure 9.1 Example of the reconstruction of an entire housing project, (Kiefhoek, Rotterdam, J.P.P. Oud, 1928-1930, demolition and reconstruction 1990-1995, situation 2009).



(a)



(b)

Figure 9.2 Reconstruction of façade panels, the house adjacent to the right still has the original panels, although painted white (Housing *Jeruzalam Frankendaal*, Amsterdam, B. Merkelbach, Ch. J. F. Karsten, P. J. Elling 1947-1949, situation 2011). a) Overview. b) Close-up of new (left) and original (right) façade panels. As the original panels are painted, the colour cannot be compared, however differences in aggregate size can be noticed.

ited knowledge of the value of the historic concrete. Awareness that concrete can be a material that needs conservation is still scarce. This is amongst others reflected in the small number of publications addressing concrete conservation (for example IFS, 2004, 2008; Macdonald, 2003; Müller et al., 2004).

Conservation campaigns are initiated when a monument shows signs of degradation and/or when its function is altered, similar to a repair campaign. Structural health, safety, and environmental factors, which are considered for choosing a repair technique, are valid as well, but must be extended by factors relevant for conservation, such as the preservation of heritage values, the role of the material as a historical archive and the extended service life, the *“heritage service life”* (see Section 9.3.4). Heritage values should not be endangered by interventions, which can easily happen when uncritically applying standard repair strategies. Concerning the quality of the repair in a conservation context, it is admitted amongst concrete repair specialists that *“quality generally takes precedence over economy and special funding can sometimes be obtained for the necessary works. Standards of work may also be higher as there is the need to meet the requirements of the approving or authorising body which may undertake their own inspections”* (Matthews et al., 2007, p. 22).

Therefore, it is not only the state of conservation and function, but especially the type of heritage value ascribed to the historic concrete that should determine the criteria for planning and evaluating a conservation strategy, which will be discussed in detail in Part III *Development and Evaluation of a Dedicated Conservation Strategy*. As values vary from building, context and culture, and as degree of damage and material properties vary as well, there is no fixed rule of what the most suitable intervention for a group of values or types of historic concrete would be, and instead case based decisions have to be made.

9.3 General requirements towards repair techniques

Repairs are applied to treat a cause of damage or symptom. Additional, conceptual requirements exist which describe desired properties of a repair material either to achieve a durable repair or to avoid side-effects. In the following sections, the main conceptual requirements will be explained both for conservation and for concrete repair: compatibility (Section 9.3.1), retreatability and reversibility (Section 9.3.2), durability (Section 9.3.3) and newly introduced the heritage service life (Section 9.3.4).

9.3.1 Compatibility

One of the challenges when choosing a repair material is to evaluate the behaviour of the two materials working together - the historic concrete and the newly introduced material -, or in other words their compatibility. Definitions exist for compatibility for both concrete repair and conservation with different emphases.

Technically, compatibility can be understood that the *“introduced treatment will not have negative consequences”* for neither the original nor the new material, and no undesired harm will occur (van Balen, Papayianni, van Hees, Binda & Waldum, 2005). A broader and less material orientated definition, which includes the influence on the heritage values and focuses on a larger scale is given in the Burra Charter: *“Compatible use means a use which involves no change to the culturally significant fabric, changes which are substantially reversible, or changes which require a minimal impact”* (Australia ICOMOS, 1999).

In both fields, concrete repair and conservation, it is criticised that compatibility is often misunderstood as to replace *“like with like”*, and the underlying details of degradation and material properties are not understood in practice (for example Van Hees, 2004; Vaysburd, 2006). In the field of conservation, the poor experience of using epoxies and acrylics for repair mortars supported the idea that the composition of a suitable repair mortar should be a copy of the original substrate (Teutonico, Charola, De Witte, Grassegger, Koestler, Laurenzi Tabbasso, Sasse & Snethlage, 1997).

Within the field of concrete repair, compatibility is mainly discussed for repair mortars (for example Beushausen & Alexander, 2007; ICRI, 1996; Vaysburd, 2006; Woodson, 2009). For other repair techniques, compatibility is discussed less frequently, although it is equally relevant. For repair mortars a new composite system is created, with the aged concrete, an interface and the repair material itself, and performance criteria developed to evaluate the compatibility, mainly dimensional (including shrinkage, thermal expansion, creep and modulus of elasticity), chemical, permeability, electrochemical and occasionally aesthetical criteria (Vaysburd, 2006). Similar criteria - mechanical, physical, chemical and aesthetical - are applied for conservation for historic (bedding) mortars (Schueremans, Özlem Cizer, Janssens, Serré & Van Balen, 2011; van Balen et al., 2005, 2003; Velosa, Veiga, Coroado, Ferreira & Rocha, 2010). In the following, some definitions of the different criteria and their importance will be discussed.

Dimensional criteria are relevant for repair mortars and affect the *“bond, ability to carry loads, durability and appearance”* (ICRI, 1996). The underlying problem is that the concrete to be repaired has already aged and will hardly shrink anymore, whereas the repair material is fresh and will shrink when drying, especially mortars with a high cement content (ICRI, 1996; Woodson, 2009). For this reason, polymer mortars are sometimes applied. When in service, repair mortars can change their dimension due to temperature changes; therefore the thermal coefficient of the repair mortar and the substrate should be similar to prevent debonding or damage of the repair (ACI Committee 546, 2006). Creep *“is a time-dependent deformation resulting from a sustained load”* (ICRI, 2010) and *“repair materials should have a creep factor consistent with the material being repaired”* (Woodson, 2009).

The modulus of elasticity is a structural factor which measures the stiffness of a material (ICRI, 1996). Its relevance depends on whether the concrete is load bearing or not. If the repair material should not carry loads, it should have a lower

modulus of elasticity than the substrate; if it should carry loads, the modulus of elasticity should be similar for the repair material and the parent concrete. When the modulus of elasticity of the repair material is higher than that of the concrete, there is the risk of damage to the concrete (ACI Committee 546, 2006).

The compressive strength stands in close relationship with the modulus of elasticity and should be approximate to the compressive strength of the concrete at the moment of repair, such that both repair and substrate can mechanically act as one material (ACI Committee 546, 2006; ICRI, 1996). Another strength characteristic, the bond strength at the interface, indicates the *“resistance of the repair material to separation from the substrate concrete, from reinforcing steel or from other materials with which it is in contact. It relates to the ability of the two materials to act as one. [...] It is essential that a repair material has sufficient bond strength to the substrate concrete such that the repair does not separate from the substrate concrete. [...] Bond strengths that exceed the tensile strength of the substrate will induce failure in the substrate if sufficient interface stresses result in shrinkage, thermal movement, or other factors”* (ACI Committee 546, 2006, p. 7). For conservation, the latter also means that too high bond strength can cause a loss of historic fabric in case of failure or during the removal of the repair material.

Chemical criteria are relevant to prevent the (re-)occurrence of damage. Some chemical degradation mechanisms tend to slow down with time as the involved components in the concrete have been consumed. If new components are introduced with the repair material, the degradation process can continue. For example, Alkali-Silica Reaction (ASR) slows down with time as the alkalis in the cement are consumed (Emmons & Vaysburd, 1994). If a repair mortar has a high alkali content and the aggregate is still reactive, ASR can continue or even be reactivated (after having slowed down). Another aspect is the pH value: when a repair mortar has a too low pH value and is placed next to the reinforcement, the risk of corrosion exist. Chemical criteria are also understood (for repair mortars) as the *“chemical composition, type of binder, binder/aggregate fraction”* (Schueremans et al., 2011).

Permeability *“is defined as the property that governs the rate of flow of a fluid [...] into a porous solid”* (ICRI, 1996). A low permeability of the surface is usually desired to prevent or reduce the ingress of chlorides and carbon dioxide to prevent corrosion. When the surface of the concrete or large parts of it is sealed with a too impermeable material, moisture present in the concrete cannot evaporate and the entrapped water can cause freeze-thaw damage to the concrete or to the repair material (e.g. coatings, repair mortars) can debond (ICRI, 1996; Woodson, 2009). For historic concrete, it has to be remembered that it can be more vulnerable to freeze-thaw damage due to the different microstructure (e.g. no use of air entraining agents, higher w/c ratio). An ideal repair material should therefore have a *“low water absorption and high water vapor transmission characteristics”* (Woodson, 2009).

Electrochemical criteria are relevant to prevent corrosion of the reinforcement. Hereby, the electrochemical behaviour between substrate and repair ma-

terial is evaluated, including the properties of the (possible) anodic and cathodic zones, such as moisture content, oxygen availability, ratio between cathode and anode, or the conductivity of the repair material (Emmons & Vaysburd, 1994). To prevent galvanic corrosion when introducing new metals next to the reinforcement, it should be considered that the reinforcement of historic concrete might have been of less noble (ferrous) metals than current reinforcement.

The aesthetical properties of a repair are mainly considered when the repair will remain visible, i.e. when no coating will be applied (ACI Committee 546, 2006). The intention is that the repaired area will not be visible from a reasonable distance and as factors mainly the colour and the texture of the repair material are discussed, and how close they match with the surrounding concrete. In standard repair projects it is normally not considered and special measures have to be made to include aesthetical requirements. Ageing and environmental factors have to be taken into account as well, especially for polymer modified or polymer mortars, as *“some repair materials will change appearance as they age due to weathering, exposure to ultraviolet (UV) light, drying or curing”* (ACI Committee 546, 2006, p. 10); in addition the colour can change depending on whether the repair material is wet or dry, making the repaired areas more visible.

The usability of the above mentioned criteria and definitions is, according to Vaysburd (2006), not always clear in practice when it comes to choosing a repair material. During this research it was observed that the required material parameters of the historic concrete are seldom determined, as detailed pre-investigations are not always carried out, and detailed criteria for a repair material not given, jeopardising the durability of the repair.

9.3.2 Retreatability and reversibility

Throughout the monument's life over decades or centuries, it is inevitable that both monument and historic material will undergo several repair cycles. Therefore, it is relevant to know whether a potential repair technique allows future (re)treatment, and if so, if the number of cycle is limited. In the field of conservation, the term retreatability has been defined as *“that the conservation treatment / repair material on the present would not preclude or impede further treatment in the future”* (Teutonico et al., 1997; van Balen et al., 2005). Retreatability replaces the previously used term reversibility, which originated from art conservation and was found unsuitable for building conservation (van Balen et al., 2005). In art conservation, reversibility is seen as *“vital for the future of objects and is a consideration in the choice of both materials and methods. An optimal treatment allows future conservators to detect added materials, remove them safely, and carry out another treatment without constraint”* (Appelbaum, 2009, p. 353). The motivation to consider reversibility was to exclude damage to the object during removal of the newly added material and that interventions can be undone if no longer considered suitable. Reversibility is seen as an active choice, allowing to remove a material at any time, even before it has failed (Appelbaum, 2009).

From the field of stone conservation, it was stated that cleaning, consolidation and protective techniques were not reversible but still necessary techniques, questioning the usability of the conceptual demand of reversibility. Irreversible interventions such as (premature) replacement of natural stone are frequently applied in practice (see for example Quist, 2011), but not noticed as irreversible, whereas the treatment of natural stone with polymer-based impregnation agents is more discussed in public (Raupach & Brockmann, 2001; van Bommel, 1999).

Therefore, a combination of compatibility and retreatability was considered as better conceptual framework (Teutonico et al., 1997). Since, retreatability is more often discussed for conservation in academic papers (for example van Balen et al., 2005), yet less for concrete repair. Retreatability should not only be understood as the possibility to reapply the same repair technique (for example several layers of coatings) but should include a review of the retreatability of the same cause of damage with different techniques.

9.3.3 Durability

The terms durability and service life (see Section 9.3.4) stand in close relationship. Durability is considered for concrete as the *“ability of a structure or its components to maintain serviceability in a given environment over a specified time”* (ICRI, 2010). The durability of new concrete structures has received much attention; the durability of repair techniques is less studied and premature failures of repairs are not uncommon (Beushausen & Alexander, 2007; Matthews et al., 2007; Tilly & Jacobs, 2007). Different types of factors influence the durability of a repair materials such as the environment it will be exposed to, the activity of degradation, the (lack of) compatibility between the new and old material (see Section 9.3.1) or the quality of workmanship.

In a European study carried out in 2003 by the CONREPNET network (Matthews et al., 2007), 230 Europe-wide cases were analysed for the durability of concrete repair; 40% of the repairs showed signs of failures between 6 and 10 years of age, yet also cases of repairs lasting up to 50 years were observed. Similar indications of premature failure are given by Vaysburd (2006, p. 675), stating that *“a successful repair, lasting 15-20 years, is a very seldom-occurring phenomenon; it is more a myth than a reality”*.

The cause of failure of a concrete repair is usually not a poor performance of the repair material itself, instead the main causes are an *“incorrect diagnosis of the underlying problem, incorrect design of repair [...] poor workmanship, use of incorrect repair materials [and] failure to follow the manufacturer’s instructions on the use of repair materials”* (Tilly & Jacobs, 2007, p. 14). Suggestions to improve the durability of concrete repairs include *“early intervention before damage is visible, proactive monitoring and maintenance in support of this, correct diagnosis of the problem and mechanism(s) causing the deterioration, effective intervention systems for preventive and remedial treatments”* (Matthews et al., 2007, p. 4).

Although the CONREPNET study refers to concrete repair and not concrete conservation, the conclusions are relevant for concrete conservation, as, in practice, materials, strategies and involved people are usually the same. Indications from the field show that it is not uncommon to carry out conservation without determining the cause of damage, or without analysing the compatibility of the repair material with the historic concrete. For conservation, the demands to preserve the historic material and heritage values can be additional challenges influencing the performance of a repair, as choices cannot be made based on the technical performance only. Premature failure can cause unnecessary loss of historic evidence and heritage values. Therefore, sound research prior to the planning of the repair is essential in order to understand as much as possible about the risks and benefits of choosing a specific repair technique and repair material.

9.3.4 Heritage service life

When planning new concrete structures, the expected service life is estimated and the design is adapted to be sufficiently durable for the required service life, considering main parameters such as exposure class and material properties, also known as service life design. Service life is understood as the period in which a structure/element fulfils its function without major unexpected interventions; service life ends when a defined unacceptable state is reached. The service life can be evaluated from technical, functional and economic points of view (for further details see Bijen, 2003; DuraCrete R17, 2000; fib CEB FIP, 2002; The European Union - Brite Euram III, 1998, 1999). For existing structures, the remaining service life is referred to when evaluating the time frame for the performance of repairs.

In practice, explicit discussion of the service life of both a monument and an intervention is rare. More common are approaches in which the emphasis is laid only on the result after the execution of the works and agreed warranty. Occasionally, interventions are, often implicitly, evaluated if they are designed according to common conservation principles such as compatibility and retreatability.

The underlying concept of integrating possible degradation risks and adapting the properties of a structure to withstand these risks for a defined period can be useful for conservation, as it is intended to safeguard monuments for following generations. A modified concept of service life, addressing durability, repair and maintenance, can be beneficial for a better evaluation of different conservation scenarios, considering both historic material and intended repair.

However, an evaluation of the service life on performance and economy based criteria as done for new structures and regular concrete repair is much too limited for a monument. Generally, historic concrete buildings have already surpassed the end of their designed service life. This does in many cases not imply that they are technically unsound, as is demonstrated by their persistence. Nevertheless, reconstruction and demolition might be a more economic option than conservation. It is evident that this would violate conservation principles. In fact, the concept of conservations implies the demand to prolong the service life of monument to an

infinite age, i.e. a perpetual heritage service life, preferably whilst preserving the historic material on-site (Heinemann, Van Hees, Nijland & Zijlstra, 2010). Challenges are the little data available on the durability of repairs of normal concrete and historic concrete in particular.

Part of a perpetual heritage service life is the occurrence of several intervention cycles. Knowledge of the durability of a repair can indicate the expected numbers of repair cycles in a given period, for example 50 or 100 years, showing the relevance of retreatability or material loss associated with each cycle, an aspect relevant for the heritage service life.

It is unlikely that the outcome of a simulation of several intervention cycles will be identical to the future state of the monument itself. Too many factors cannot be predicted, such as societal changes related to the heritage values and the (economic) possibilities to maintain heritage, new repair techniques that might be developed, or unpredicted external events that can cause further damage. Some likely events can be predicted such as the normal continuation of the ageing process of the material, or which repair techniques will be excluded for future use by a decision made now. The relevant point is to create awareness of present day choices and to fully understand their possible consequences.

Another aspect is that monuments are not museum objects and should be functional. To ensure conservation, adaptation to a new function will often be necessary - in many cases not once but many times - as one of the best ways to guarantee a perpetual heritage service life is to avoid vacancy and accompanying degradation. Additionally, several intervention cycles will occur, each with their own potential problems of failing repair materials, increased deterioration and emphasis on heritage values and material aspects to preserve. In total, the following aspects should be considered:

- Preservation of heritage values.
- The remaining service life of the original fabric.
- The frequency, extent and impact of future interventions.
- The situation at the end of the service life of a repair/intervention.
- Possibilities and necessity of changing functions.

An advantage for concrete conservation is that existing prediction models for corrosion of normal reinforced concrete can be used as starting point, using the specific materials properties of historic concrete (e.g. used binder, thickness concrete cover, porosity). Less reference data exists on the long-term consequences of interventions of historic concrete; a short-term solution is an approximation based on experience and reference objects (both conventional repair and conservation), and additional try-outs or even ageing tests of interventions. To improve our understanding of the long-term performance of historic concrete and its repair, better documentation and evaluation of interventions is imperative.

9.4 Repair techniques

The choice of an appropriate repair strategies, repair technique and material is influenced by several factors, such as the environment, the underlying cause of damage, the desired remaining service life, costs and availability, the structural performance, the safety and usability of the structure. These criteria must be formulated and evaluated by the respective expert and are valid for both repair and conservation. For conservation, the impact of a repair technique on the historic fabric and heritage values forms a very important, additional criterion, yet in practice little reference is given. A general overview of the impact of repair techniques on historic concrete is given in Macdonald (2003) but focuses mainly on the surface and appearance of different repair materials.

In the following sections, repair techniques are reviewed for their impact, the possibilities of modification (e.g. appearance), and indications of the consequences of failure or successive repair cycles. Another relevant aspect is the impact of concrete removal, which for most techniques is necessary as preparatory works. Due to the complexity of the field and the diverging properties of the historic concretes and of the conservation aims, the following overview cannot give certainty for the choices to be made in an individual conservation project. Instead, it is a guidance to consider the risks and benefits of different techniques and to initiate discussions among the different parties involved in the conservation about possible conservation strategies, which will be further discussed in Part III of this thesis.

9.4.1 Concrete removal

Historic concrete has to be sometimes removed, either as part of sampling for material research, and as preparatory works for repairs. Samples taken for investigative purposes, such as determining the material composition, cause of damage or effectiveness of a treatment, are relatively small. Despite being (minor) destructive, sampling can be beneficial as it can help to determine the cause of damage and give information on the required properties of possible repair techniques, and thereby support the preservation of the historic material. In the draft prEN 16085:2010 *Conservation of Cultural property - Methodology for sampling from materials of cultural property - General rules*, it is demanded, that “the sampling should be done so as to minimize any visible and/or disrupting/damaging effects and taken when possible from an inconspicuous place provided that it fulfils the aim of sampling. Sampling requires manual skill and knowledge of the type of cultural property in question and collaboration with the decision making team. [...] Only a minimum number of samples should be taken.” The number and size of samples should be chosen balancing unnecessary material loss and obtaining sufficient information for a correct diagnosis, as otherwise there is the risk of failure of a repair. The repair of the damages caused by the sampling should not stand out (Figure 9.3).

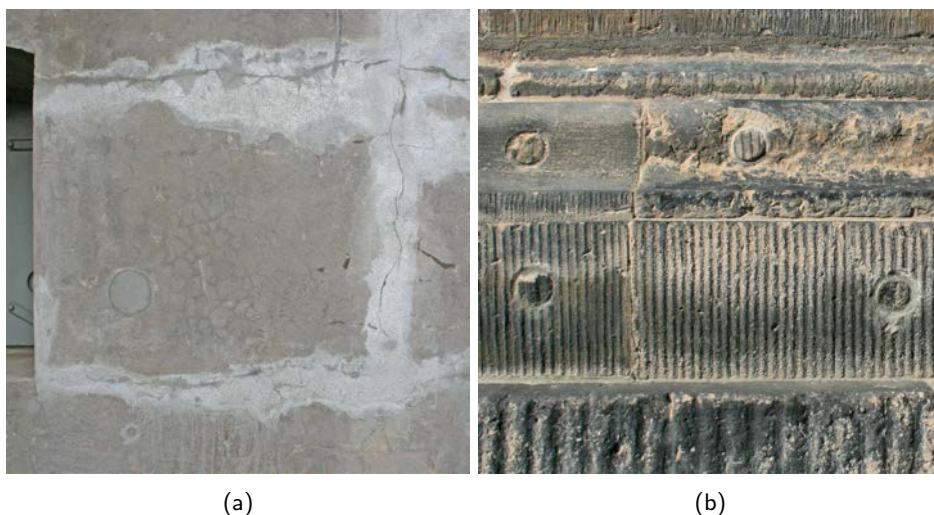


Figure 9.3 Example of the impact of taking cores on the appearance. a) The location where the core was taken is still visible as the colour of the repair mortar is darker than the surrounding render (Fort Bezuiden Spaarndam, 1897 - 1901, situation 2008). b) The holes made by the core can sometimes be closed by the original material, in this case natural stone, yet caution has to be given to place the cores at the original location and their original orientation (Church of Our Lady, Dresden, plinth, situation 2011).

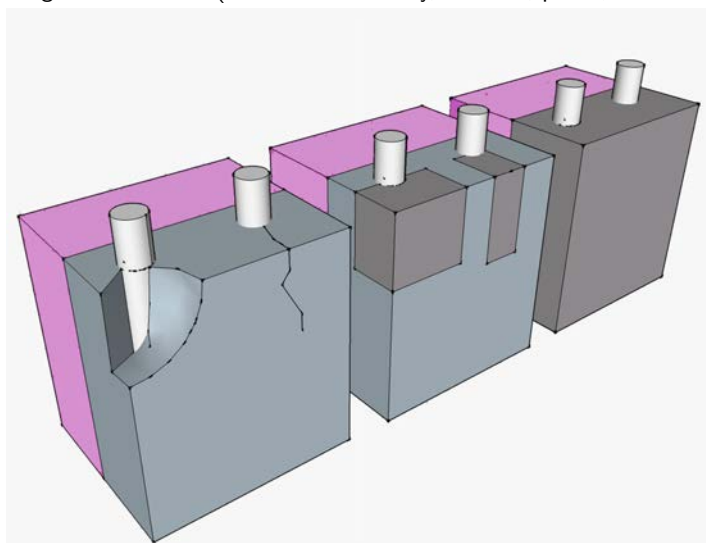


Figure 9.4 Schematic drawing, comparing of concrete removal for different treatments of corrosion induced by carbonation. Left: initial situation with spalled and cracked carbonated concrete (grey) and uncarbonated concrete (pink) behind rebars; middle: local repair where only damaged concrete is removed, leaving the carbonated concrete that is otherwise sound; right: total replacement of carbonated concrete.

For preparatory works before repairing concrete, historic material sometimes has to be removed. The amount is influenced by the underlying cause of damage and chosen technique. For example Figure 9.4 shows the situation of a concrete which is damaged due to carbonation induced corrosion. A removal of only the cracked concrete and leaving the carbonated concrete in place does not eliminate the risk of further corrosion and can cause early failure of the repair, if no other measures such as an electrochemical repair technique (see Section 9.4.5) would be applied to prevent corrosion. A total replacement of the carbonated concrete near and behind the rebars can restore the alkalinity near the reinforcements to prevent corrosion.

What can be encountered in conservation practice is a well-intended limited removal of carbonated concrete with the idea to preserve more historic material, yet without taking extra measures to prevent further damage (for example modification of the environment, protective surface treatments) and thereby risking a propagation of damage, further material loss and early failure of the repair. The amount of material removal stands in close relationship to the chosen repair approach and the expected remaining life of the historic material on-site. In such a case, it has to be considered what is most important: a longer service life of the repair coming with the price of an initial relatively high loss of original fabric, a less durable repair with more frequent repair cycles which will cause a loss of historic material at the interface during each removal, or an initially more expensive intervention with less repair cycles and less material loss.

For conservation, it is important to understand the heritage values related to the historic concrete (see Chapter 8 *Mutual relationship between the heritage values, historic concrete and state of conservation*). This insight should be used to evaluate the possible benefits and risks of removing historic material for both, the technical performance and preservation of heritage values. Not only the impact on the historic concrete itself should be considered but also on other historic materials attached to the concrete, such as historic paintings or renders. A balance between preserving the historic material and the treatment of the cause of damage has to be found. The quantity of repair cycles must be taken into account as well, including the impact of the removal and/or failure of a repair when comparing initial material loss and material loss after a specific period.

In the following, some examples of common material removal during concrete repair are discussed. Depending whether the concrete has only to be removed superficially, in depth, or cleaned, different techniques exist. Besides secondary damage such as micro cracking, the possibility to control the amount of removal should be considered in order to guarantee that not too much material is removed, especially when the concrete is of a lower strength or of a high historic value.

Large-scale removal of cracked and carbonated historic concrete is not uncommon for conservation (Figure 9.5 and Figure 9.6), especially when decisions are mainly based on technical aspects and the possible heritage values of the historic concretes not understood. In case of patch repair of exposed concrete, the edges of damaged areas might have to be modified, either to disguise the joint between

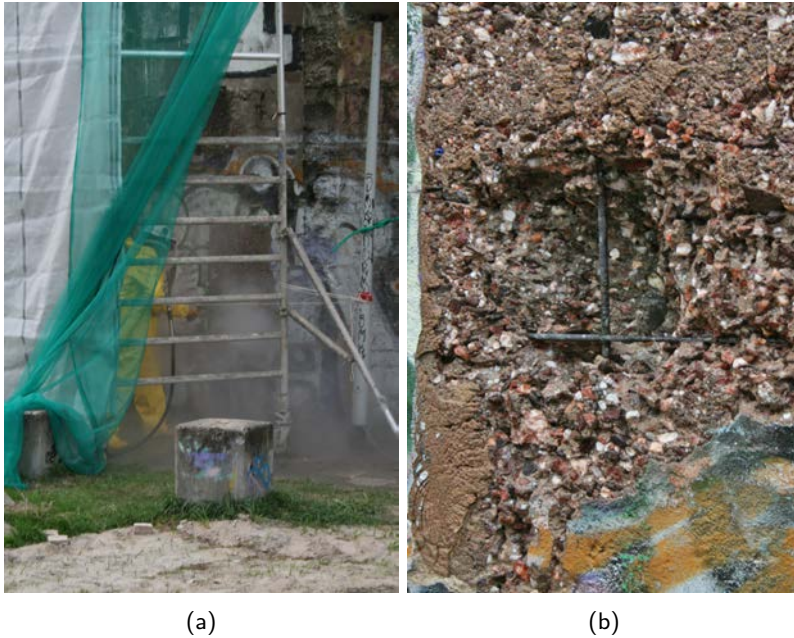


Figure 9.5 Demonstration of hydrodemolition on a historic concrete structure (Hofplein railway viaduct, Rotterdam, Van Hemert, 1900-1908, situation 2009). a) Overview of the hydrodemolition process. b) Close-up of the result showing a deep concrete removal.



Figure 9.6 Large scale concrete removal with hydrodemolition (circumambulation passageway of the Pilgrimage church in Brielle, H. Goossens (reconstruction), E.J. Margy, 1912, situation 2010). a) Overview of concrete rafters, partial concrete removal. b) Column after removal of the entire original surface and most of the original concrete, exposing the reinforcement.

old and new in a less prominent spot or the depth might have to be increased to be able to use the correct coarse aggregate size. Technically, a modification of the geometry of the patch repair can be advisable to reduce stresses around corners of the patch. Secondary reinforcement, such as shrinkage reinforcement, is sometimes removed during repair when the original concrete cover is too little and thereby to reduce the risk of corrosion (Müller, 2010; Schmidt, 2010). However, it has to be kept in mind that the secondary reinforcement can be a relevant historic fabric, and its significance should be understood before deciding about eventual removal and if no measures exist to preserve it.

Concrete surfaces are cleaned before the application of a surface treatment or when the appearance of the surface is disliked due to soiling or presence of deposits. In a comparative study on cleaning methods for historic concrete, it was shown that cleaning can modify the texture and colour of the concrete, and that not all techniques are equally efficient and therefore the choice depends on the desired cleaning level (Marie-Victoire & Texier, 1999). Attention has to be given to the aggressiveness and effectiveness of the cleaning technique, for example fine textural features of the surface or remains of historic paints should not accidentally be destroyed.

9.4.2 Repair mortars

Repair mortars are the most commonly used concrete repair materials. Whereas for normal repairs, concrete replacement using repair mortars to treat corrosion are recently being substituted more often by electrochemical methods (Tilly & Jacobs, 2007), they still form the major group for concrete conservation. They can either be applied by hand, sprayed or cast. They are used to replace lost or damaged concrete for structural strengthening, and to increase the physical or chemical resistance (see NEN-EN 1504-09:2008). The types of repairs carried out are often overlays and concrete replacement. They are sometimes used in combination with other techniques, such as cathodic protection or coatings. In case repair mortars are applied to treat corrosion symptoms, a protective coating of the reinforcement bars can be applied. Yet, one should note that a coating of the reinforcement might exclude a (future) electrochemical treatment. Small scale repairs with mortars are informally called patch repairs (ACI Committee 546, 2006).

The composition of a repair mortar is in principle similar to the composition of a normal mortar: binder, fine aggregates, water and maybe admixtures and additives. In case coarse aggregates are used, one speaks of a repair concrete. The mortar composition should be determined by the properties of the parent concrete, including the appearance if required. A repair mortar applied to an existing concrete structure will interact with the parent concrete. This interaction can be beneficial, as it can prevent further degradation or, in case of a structural repair, restore the strength of the concrete member. If the repair mortar does not have the right properties, it can be harmful.

Many discussions on the compatibility of concrete repair materials focus on repair mortars and have been addressed in Section 9.3.1. Compatibility can be influenced by choosing a similar binder and aggregate for the repair mortar as in the original concrete. The new material should not be superior to the original material *“in terms of strength, carbonation resistance, permeability, and diffusion resistance”* (Wood, 2011, p. 86). Other determining factors are the geometry and size of the area to be repaired, if the repair is structural or non-structural, the method of application, the environment the repair will be exposed to, and the underlying cause of damage.

To be able to design a suitable repair mortar mix which is compatible with the parent concrete, it is necessary to determine the relevant properties of the original concrete: compressive and tensile strength, the elastic modulus, the used binder and original mixing proportions, and if the repair will remain visible, the surface texture, including erosion of the original concrete surface; the colour of the mortar matrix, the type, colour and grading of the aggregates should be identified (Günter, 2010). In practice, the level of pre-investigation necessary to obtain the required data of the original concrete should remain in proportion with the size of the repair area, the significance of the historic concrete and the required appearance.

One main problem of repair mortars is drying shrinkage, which by stress restrains could cause damage to the parent concrete, or in case of a cracking of the repair mortar, could allow the ingress of harmful agents, loss of adhesion and eventually of debonding. Countermeasures are to use coarse aggregates in the repair mortar/concrete and proper curing, or the use of special admixtures (ACI Committee 546, 2006). Other reasons to modify the mix of a repair mortar are to improve the workability (Figure 9.7), rapid strength development and durability of the repair. In practice, three main groups of mortars are used for concrete repair: cement-based repair mortars, polymer-modified cement mortars and polymer mortars.

To cement mortars or cement concretes, no polymers are added and they can have rather similar properties to the parent concrete, yet, especially when no coarse aggregate is added, they may crack due to shrinkage. Admixtures might be necessary to avoid shrinkage, and good workmanship, including curing, is required (ACI Committee 546, 2006; CUR, 1997b; Reed et al., 2008).

Polymer-modified repair mortars are based on a cementitious binder such as Portland cement to which 10 – 20% by mass of polymers are added. The permeability can be reduced, the corrosion protection and bond strength increased, yet these mortars are considered to be harder to place and to finish. When as polymer epoxies are used, the colour can change when exposed to UV-light as shown in Figure 9.8 (ACI Committee 546, 2006, CUR recommendation 55, 1997c).

Polymer mortars are made with an organic polymer, often an epoxy, as binder and not a mineral binder (e.g. Portland cement); however Portland cement can be added as filler. Its advantages are considered to be *“low shrinkage as it cures, good bond strength, low permeability [...] and good resistance to chemical attack. It also sets quickly reducing the downtime of the repair area.”* (ACI



Figure 9.7 Trial repair of three columns to test the workability (sprayed and poured polymer modified repair mortar) and quality of the surface finish (circumambulation passageway of the Pilgrimage church in Brielle, H. Goossens (reconstruction), E.J. Margy, 1912, situation 2010).



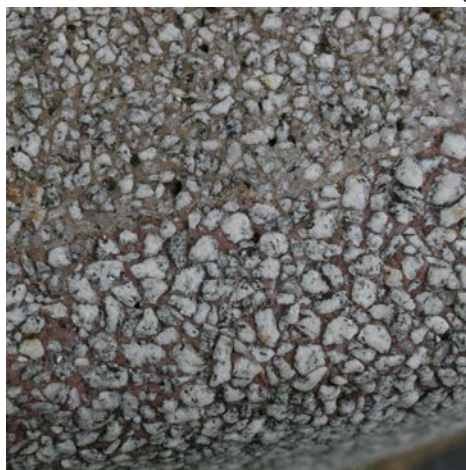
Figure 9.8 Column of an exposed concrete repaired with a polymer-based patch repair, showing discoloration due to ageing (Faculty of Architecture, TU Delft, architectural firm van de Broek & Bakema, 1960-1970, building burnt 13.05.2008, situation 2007).

Committee 546, 2006). The disadvantages are the higher coefficient of thermal expansion and a significantly different modulus of elasticity than the parent concrete, and its rather different appearance than concrete (ACI Committee 546, 2006). In this context, the lower permeability of polymer (modified) repair mortars should be considered as moisture could be entrapped behind the repair material. Another aspect which disfavours the use of polymer mortars is their lower electrical conductivity, as this excludes the use of electrochemical repair techniques.

Repair mortars can be adapted in colour and texture to the parent concrete. The adaptation of mortars to the original concrete and a reconstruction of the original surface is one of the few aspects more commonly discussed for the conservation, and for the repair of architectural, exposed concrete surfaces. Yet in practice, a close match to the parent concrete is not always achieved (Figures 9.9 to 9.11), and mismatching repairs are still frequently encountered (Figures 9.12 and 9.13).



(a)



(b)



(c)

Figure 9.9 Column foot made from decorative concrete with local repairs (Main entrance Zoo Blijddorp, Rotterdam, S. van Ravesteyn, 1939-1941). a) Overview column foot, the lighter coloured repair areas stands out from a distance. b) Close-up of column foot showing the use of a more reddish mortar with slightly larger aggregates for the repair than the original, more beige coloured mortar. c) Detail of the base of the column with a too beige repair.

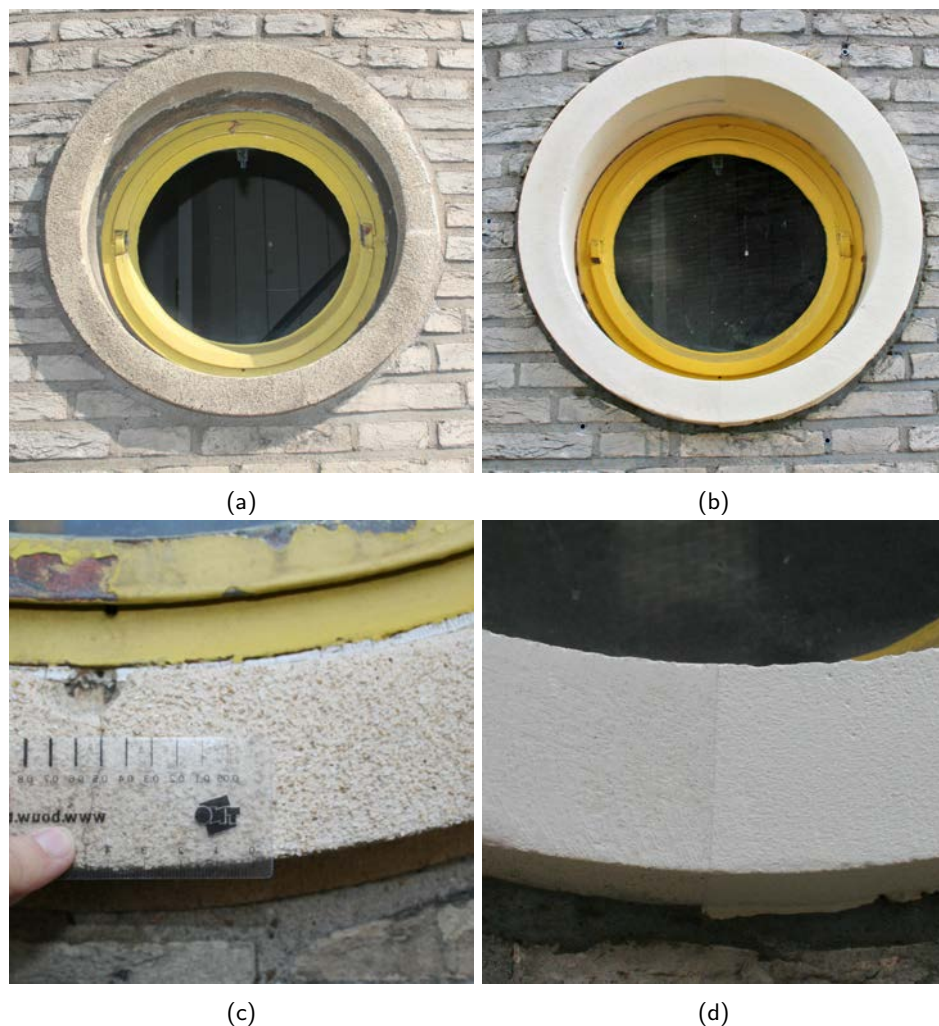


Figure 9.10 Window opening made from prefabricated concrete elements, before (2009) and after (2010) trial repair (Railway station post office Arnhem, H. Engberts, 1955-61). a) Overview window before repair. b) Overview window after trial repair with two different mortars. c) Detail original surface. d) Detail of the two trial repairs: right half using a grey repair mortar which was painted afterwards, left half using a coloured mortar. Neither try-outs used the original aggregate (flint), binder (white Portland cement) or pigment (limonite), nor washed out the surface.



Figure 9.11 Repair of an exposed concrete surface made with blast furnace slag cement and gravel, originally with a wood grain structure. Although several try-outs were made, locally the patch repair can still be distinguished due to the lighter colour and irregularly pressed-in aggregates. The wood grain texture was not reconstructed (Pumping station Parksluizen, Rotterdam; G. J. van der Grinten, 1967, situation 2010).



Figure 9.12 Concrete made with diabase as aggregate and bush hammered surface with chiselled margins which was repaired with a grey, smooth repair mortar (housing, 1930s, exact date and architect unknown, Rotterdam, situation 2011).



Figure 9.13 Column with exposed aggregate surface finish and standard grey patch repair (Train station Zutphen, H.G.J. Schelling, 1952, situation 2009).

The surface finish of the historic concrete requires special attention to be reconstructed. Tooled surface finishes allow a better adaptation in texture and colour, considering the use of craftsmen with the experience to (manually) tool concrete or natural stone. In such cases, however, it should be considered if the repair mortar can be tooled without debonding or cracking and the risk of a lower permeability of the repair. Local repairs with formwork imprints require more preparation, especially when a wooden grain texture is desired which blends in with the surrounding concrete. Wooden formwork finishes have already been often imitated by either imprinting the grain structure on the repair mortar after placing it, or by casting the repair mortar into a wooden formwork. Yet this requires a detailed survey of the original surface to determine the size of the originally used individual formwork boards, such as their orientation, the type of joint between the individual boards and the desired degree of the erosion of the grain texture. For this, specially produced matrixes can be made to reproduce the original texture by making an imprint of the surface before its removal. These matrixes are then pressed into the fresh concrete repair surface (Schmidt, 2010; Walter, 2008).

The colour of the repair mortar can be modified through these parameters: binder, pigments (including ground natural stone), aggregates (shape, grading, type, colour, and quantity), water content, curing, and surface finish. Detailed material investigation, such as petrographic analysis, can help to identify the binder and aggregates. The colour of the parent concrete can also be determined on-site with colorimetric instruments (Müller, 2010). The pigment type can be identified with petrographic analysis in case mineral pigments or ground natural stone were used; for iron oxide pigments, other investigation methods are necessary, such as scanning electron microscopy (SEM) or possibly X-Ray diffraction (XRD). If the original binders and pigments are no longer available, a similar appearance of the repair mortar can be achieved by combining white Portland cement with iron oxide pigments and aggregates with similar mineral composition and colour (Müller, 2010). It should be remembered that the curing of the repair mortar influences the colour, and that colour differences between original concrete and repair mortar can increase in time due to different ageing behaviour.

The maximum aggregate size depends on four main factors. First, large aggregates are considered beneficial as they reduce the shrinkage of the repair mortar. Second, the depth of the cavity to repair limits the maximum size, as the aggregate diameter cannot exceed the depth of the repaired area. Third, in case of exposed concrete, an aggregate size similar to the size and grading of the parent concrete is desirable, and finally the application method, as the aggregate size is limited when the mortar is to be sprayed or manually applied. For decorative concrete it might be necessary to use rather small aggregates as often only the smaller fractions of coarse aggregates were applied (see Figure 9.9). In such cases an increased shrinkage risk has to be considered and counter measures taken (for example different mix, amount of curing, use of modifying admixtures). In case of repair of an exposed aggregate finish, the extent of the damaged area might be too small to allow the use of the right aggregate size. This can justify a deeper removal

of concrete to use an aesthetically correct aggregate size, while still considering the heritage values to preserve. To achieve aesthetical compatibility, the use of two layers, one structural, corrosion controlling layer, and a cosmetic top layer can be possible (Wood, 2011).

The desired repair thickness influences the method of application and the composition of the repair mortar. Technical demands for a thick concrete repair can be an increase of the cover thickness to reduce the corrosion risk or to increase the strength of the concrete member.

Sprayed concrete is used for large scale repairs where manual application of the mortar would not be economic, such as soffits and vertical surfaces (see Figures 9.14, 9.15 and 8.22). Hereby, repair mortars are sprayed pneumatically on the surface (CUR recommendation 53, 1997a; NEN-EN 14487:2005). The terminology for sprayed concrete varies, and the terms guniting and shotcrete are commonly used. Shotcrete is sometimes defined as a dry sprayed concrete (Broomfield, 2007) or as the American definition (Taylor, 2011); guniting is defined as wet sprayed concrete (Broomfield, 2007) or as the British definition (Taylor, 2011). In the context of European harmonisation the term sprayed concrete is used (NEN-EN 14487:2005, Taylor, 2011).

To reduce the shrinkage of the sprayed concrete, fibres can be added to the mortar or a wire mesh applied on the surface. Before application, the surface must be cleaned and roughened to enhance the bond between mortar and parent concrete (CUR recommendation 53, 1997a). The thickness of the sprayed concrete layer over the reinforcement should be in agreement with the guidelines of concrete cover and depends on the environmental class but can be reduced in combination with a protective coating (CUR recommendation 53, 1997a). This aspect has to be carefully considered in case the historic concrete structure has originally a lower concrete cover, including the possible side effects of either changing the geometry by increasing the cover or the visual impact of a protective coating.

The composition of the mortar is more limited for sprayed concrete, especially the maximum size of the aggregate, which is restricted by the size of the nozzle of the spraying gun and the thickness of the sprayed concrete layer. General advices are of a maximum size of up to 10 mm (Taylor, 2011). Recommended maximum aggregate sizes are either $\frac{1}{3}$ of the thickness of the sprayed concrete layer, $\frac{1}{3}$ of the designed thickness of the new concrete cover, and max. $\frac{1}{4}$ of the distance of the rebar in the sprayed concrete layer and the distance between the rebar and the substrate (CUR recommendation 53, 1997a). For concrete conservation projects, try-outs have been made to use aggregates of 16 mm to match the repair areas aesthetically to the surrounding parent concrete (Figure 9.14, Rassek & Rubba, 2008). The impact of a sprayed concrete on the original material and surface is generally great, as large area of the original surface will be covered and all details of the original surface lost (e.g. original paints, tooling, see also Figure 7.29). However, the sprayed concrete can be modified to imitate the original surface to a certain extent, tooled and formwork marks can be pressed into the freshly applied surface.

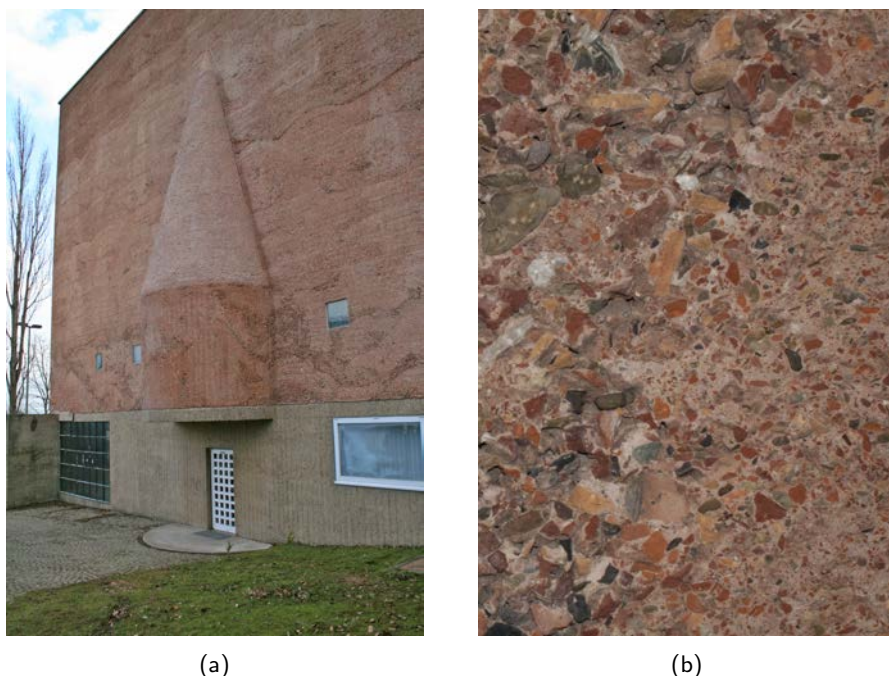


Figure 9.14 Example of using sprayed concrete with a specially adapted repair concrete to reconstruct the roof of the conch of a church (Fatima church, Kassel, Germany, G. Böhm, 1957-1959, situation 2008). a) Overview of the façade with the repaired roof. b) Close-up of the repair mortar, showing the use of broken bricks as aggregate and ground brick to match the original composition which was made with brick debris.

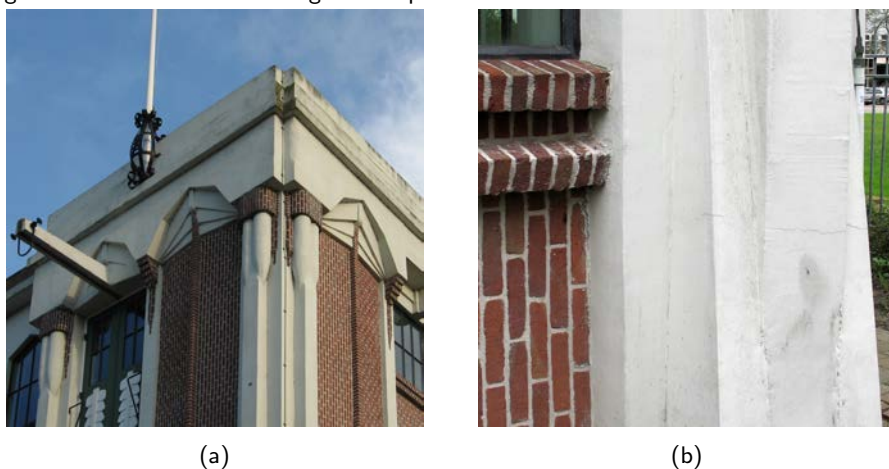


Figure 9.15 Example of a large scale surface repair with sprayed concrete with possibilities to reconstruct the concrete ornaments, the original surface finish is unknown (storehouse Mercurius, Wormerveer, M.J. Stam, 1919, restoration 1995-1997, situation 2006). a) Overview ornaments. b) Local cracks are visible on the surface of a column.

The underlying cause of damage should be considered when choosing a repair mortar. Repair mortars are often used to restore lost areas of concrete due to damage symptoms such as spalling. They can be used to replace carbonated concrete near the reinforcement if corrosion is to be treated, however less destructive, electrochemical techniques are possible as well (see Section 9.4.5). In case of corrosion due to chlorides and when no electrochemical techniques are applied, the surrounding chloride contaminated concrete should be removed if the boundary conditions are favourable for corrosion (e.g. CO_2 , sufficient relative humidity) to prevent the appearance of an incipient anode problem: the concrete surrounding the patch repair is still contaminated with chlorides, but the previously corroding reinforcement in the repaired zone cannot function anymore as an anode. Instead, the adjacent reinforcement in the chloride contaminated zones becomes the anode, initiating corrosion and causing a wandering of the corrosion zone to the area adjacent to the repair. To avoid such secondary damage, it is advised to apply patch repair of chloride damage in combination with cathodic protection (Broomfield, 2007; Raupach, 2006). These side-effects have to be kept in mind when planning a patch repair of historic concrete, and considered if chloride can be present, either due to the environment or if it was added during construction, either as an accelerator or during construction at low temperatures (see Section 5.4 *Admixtures and additions*), or as (unintended) contamination of raw materials.

In case corrosion was induced by carbonation, it is common practice to remove all carbonated concrete near the reinforcement bars, even if it is structurally sound, to ensure the reinforcement will be in an alkaline environment after repair (Figure 9.4). If less carbonated concrete is removed, electrochemical techniques have to be applied, the ingress of H_2O prevented (hydrophobic impregnation, Section 9.4.4), the environment modified or a shorter service life of the repair has to be accepted, with the risk of causing damage to the original concrete and reinforcement.

The durability of repairs is strongly influenced by the understanding and elimination of the cause of damage, the workmanship and the composition of the repair mortar in relation with the parent concrete. Poorly designed or executed repair mortars might only last a few years (Figures 9.16 and 9.17), whereas during the CONREPNET project repairs lasting 20 to 50 years were observed as well (Tilly & Jacobs, 2007, 2011). The failure of a repair can lead to delamination and cracking of the mortar, corrosion of the reinforcing steel, loss of load carrying capacity and a poor appearance.

The causes for premature failures are found, on the one hand, mainly in the planning (e.g. environmental and structural conditions) and in workmanship (Beushausen & Alexander, 2007; ICRI, 1996; Matthews et al., 2007; Tilly & Jacobs, 2007). Causes for failure of a repair mortar can be differential shrinkage, which can be influenced by the water/cement ratio and the aggregate/cement ratio of the repair mortar (Wood, 2011). In the case of high (mechanical) stresses, failure will occur in the weaker material, and if the repair material is too strong, it would be in the historic concrete. During the CONREPNET project, it was



Figure 9.16 Detail of a corner of a concrete slab, the repair mortar has cracked in less than 6 years after repair and is visible due to soiling (Sanatorium Zonnestraal, Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928, restoration began in 2001, situation 2007).



Figure 9.17 Corner of an exposed concrete sculpture showing a cracked repair mortar with rust stains, indicating ongoing corrosion (sculpture by C. Visser, TU Delft, 1966, situation 2006).

shown that polymer modified patch repairs performed only slightly better than cementitious repair materials (Tilly & Jacobs, 2007). For conservation, such data are relevant, as pure cement and not polymer-modified cement mortars or concrete are considered more suitable to fulfill conservation demands (Danzl, 2008).

When repairing historic concrete, it has to be understood which material parameters can deviate from modern concrete and to what extent normal repair materials would be suitable. The influence of different binders, the higher porosity, possibly used pigments and varying surface finishes has to be understood. As the field is still recent, little data and experience of the repair of historic concrete is available, and extra attention in a conservation process is required; for example, to what extent a proposed design mix is technically compatible, especially as there is a strong tendency to use prefabricated mixes designed for modern concretes. However, case studies from different countries show that specifically mixed repair mortars for historic concrete are possible, either using the same aggregate type and size, similar binder or modifying the colour (for example Baumstark, 2004; Gaud-

ette & Slaton, 2007; IFS, 2004, 2008; Müller et al., 2004; Tyler, 2004). As most cases were published shortly after the completion of the repair works, little data is available on the long-term performance of such repaired concretes in the field, yet it shows that a re-mixing of historic concretes can be possible while achieving a suitable workability.

An example for the required further development and research for suitable repair mortars can be seen in the development of repair mortars for historic masonry in the last decade (Schueremans et al., 2011; TC 203-RHM, 2009; van Balen et al., 2005, 2003). Yet not all experience can be transferred to historic concrete due to the differences between a mortar used for masonry and used for concrete. A concrete repair mortar might have to prevent further corrosion, and the area to replace is often larger than a pointing of masonry, increasing the risk related to shrinkage. In terms of composition, concrete repairs might require coarser aggregates and the used binders differ, and have to be adapted in texture. However, a lesson to be learnt is that historic concrete structures might require specifically mixed mortars based on a study of the properties of the historic concrete, and that sometimes local aggregates have to be used.

9.4.3 Concrete injection

Weak spots in the concrete surface and matrix (cracks, voids or interstices) allow the ingress of harmful agents (e.g. H_2O , CO_2 , and chlorides). This may lead to degradation, and depending on the severity, endanger the safety of the structure. Replacement of the weaker concrete is not always necessary; instead, the concrete can be injected and by this the concrete structurally strengthened and the permeability decreased. As injection material, hydraulic and reactive polymer binders (for example epoxy resins, polyurethane resins, acrylic gels) are available (CUR recommendation 56, 1997d; NEN-EN 1504-09:2005). The choice of the injection material depends on whether it has to carry loads, be ductile or swelling, the size and activity of cracks, and the moisture content of the concrete. In case of structural strengthening, epoxy resins are preferred; in case of sealing seepages, polyurethane resins are more commonly used. Attention has to be given to the fact that the use of epoxy based resins excludes the (later) use of electrochemical repair techniques (see Section 9.4.5). Concrete injections are not reversible as they penetrate into concrete and cannot be removed without a large loss of original material. However, they allow a longer presence of the original concrete on-site.

Some material loss is nevertheless necessary when injecting concrete. As preparation, cracks have to be cleaned from debris and deposits to enhance the bond between grout and concrete; they must also be cut and sealed. Additionally, holes have to be drilled into the concrete near the crack as the material is not injected into the crack but from the side through so-called injection ports. After finishing the works, the port holes and the injected cracks remain visible on the surface (Figure 9.18). A close aesthetical match of the grout and parent concrete is diffi-

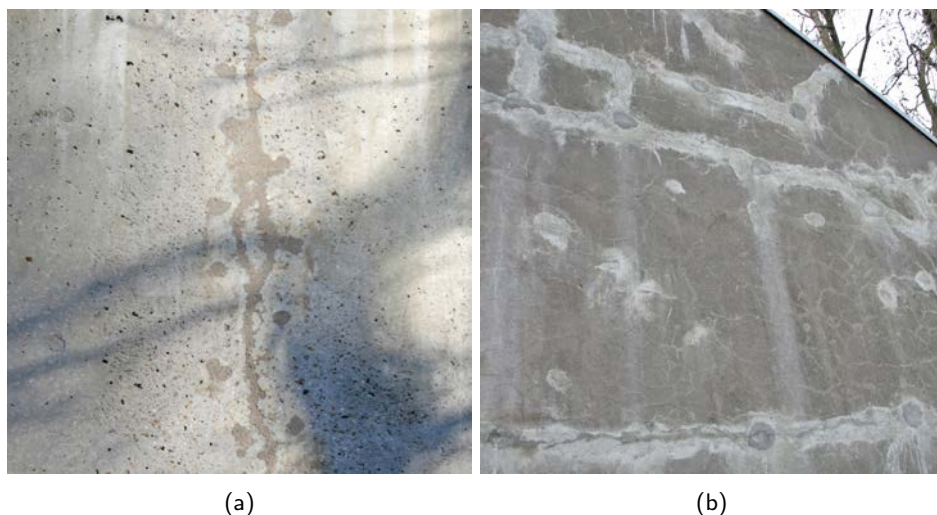


Figure 9.18 Examples of a crack injection with visible injection ports. a) Faculty of Civil Engineering, TU Delft, architectural firm van den Broek & Bakema, 1964-1975, situation 2006. b) Fort Bezuiden Spaarndam, 1897-1901, situation 2006.

cult as no coarse aggregates can be used, yet an adaptation of the colour should be considered.

Limitations for the usability of injections for historic concrete are mainly related to a possible higher porosity, more voids and inhomogeneity of the concrete due to previous mix design rules and construction methods. In such cases it has to be evaluated whether the treatment can be effective and if the concrete can be injected adequately. Problems to inject a historic concrete adequately were encountered during trials at *Fort Bezuiden Spaarndam* in the 1990s when injecting a plain concrete wall (1.5 m thick) with a high porosity, interstices and voids (see Figure 9.18b)

9.4.4 Surface treatments

The application of surface treatments, and in particular coatings, on historic concrete structures is very often disliked for their impact on the appearance. The arguments against their use is that they cause a too uniform appearance of the concrete, and even assumed transparent coatings are criticised for their shiny effect on the surface (for example Hinterthür, 1997; Van der Zanden, 1997). Before categorically excluding coatings as a repair material for concrete conservation, their potential to prevent or reduce further degradation and their degree of impact should be discussed.

Different methods are used to treat the surface of concrete: hydrophobic impregnation, impregnation, and coating, which differ in their objective (reduce per-

meability for aggressive agents such as carbon dioxide or chlorides, increase physical or chemical resistance, moisture control, enhance aesthetics), the material used (polymers or cementitious material), and their thickness, from μm to a few *cm* in case of cementitious coatings (Bertolini et al., 2004; Hurley, 2011; NEN-EN 1504-02:2004).

Hydrophobic impregnation aims at treating the “concrete to produce a water-repellent surface. The pores and capillaries are internally coated, but they are not filled. There is no film on the surface and there is little or no change in its appearance” (NEN-EN 1504-02:2004). Hydrophobic impregnation decreases the capillary absorption and the ingress of dissolved aggressive agents, yet gas can enter into and leave the concrete as the pores are left open. Such treatments are also known as water repellent treatments. The properties of the concrete which influence the efficiency of the treatment is the density and the strength of the concrete as they influence the penetration depth, with less dense and weaker concretes showing a deeper penetration. As materials mainly silicones, silanes and siloxanes are used (Bertolini et al., 2004; Polder, Borsje & De Vries, 2001).

Impregnation “reduce[s] the surface porosity and [...] strengthen[s] the surface. The pores and capillaries are partially or totally filled” and “the treatment usually leads to a discontinuous, thin film on the surface” (NEN-EN 1504-02:2004). These types of techniques are also referred to as pore blockers. A historic method for impregnation is the treatment of a surface with silicates or silico-fluorides; for example Kessler fluates have been used to strengthen natural stone or later with special mixes (*Fluoziment*) for concrete enabling early painting of the surface (Fröde, 1910, see Section 7.3.2). For similar reasons and to block the pores of the concrete, potassium silicate solutions (or waterglass) can be applied on concrete. By blocking of the pores, there is the risk that water vapour is trapped in the concrete, increasing the risk of frost damage, and of efflorescence (Bertolini et al., 2004). As the silicates react with the free portlandite in the concrete, the treatment cannot be removed without removing the reacted zone of the concrete.

Coatings can be used to protect the concrete from ingress of carbon dioxide or chlorides, to improve the physical resistance and the surface appearance, and in a preventive way in the case of anti-graffiti coatings. Coatings are defined as a “treatment to produce a continuous protective layer on the surface of concrete” (NEN-EN 1504-02:2004). The binders used for the coatings can be “organic polymers, organic polymers with cement as a filler or hydraulic cement modified with polymer dispersion” (NEN-EN 1504-02:2004). They can be used to delay the initiation of corrosion as they reduce the permeability of the surface and thereby reduce the ingress of harmful agents, either of a new concrete or of a freshly repaired concrete, but they cannot stop on-going corrosion.

Other indications for their use is cosmetically to cover up the patchy character of a repaired surface (Broomfield, 2007). To reduce the moisture content inside the concrete, coatings are designed to prevent the ingress of water but allow the escape of moisture in form of vapour. If an additional water source is present, the moisture content can increase in the concrete as it cannot evaporate quickly enough,

increasing the risk of entrapped moisture. Anti-carbonation coatings are designed to let water vapour pass in both directions, but not carbon dioxide (Bertolini et al., 2004; Reed et al., 2008). Cementitious coatings have a low permeability and are either a few mm or a few cm thick, the latter is usually considered as a sprayed concrete (see Section 9.4.2). They are commonly polymer modified to decrease their permeability and to increase the bond with parent concrete. A service life of 10 years is possible but depends on the material used (Bertolini et al., 2004).

The direct impact of surface treatments mainly affects the appearance of the concrete, especially colour, texture and gloss of the surface as well as the visibility of concrete constituents (see Figures 9.19 to 9.22). The appearance of coatings can be modified, pigments can be added, and different shades of “concrete grey” are available. However, the appearance of the treated concrete becomes more uniform than the original concrete and small colour nuances due to visible aggregates or weathering will disappear.

Preparatory treatment of the surface is required to ensure the performance. Common steps are to clean the surface, to remove loose parts of concrete, and to fill cracks and voids. The roughness of the surface might have to be reduced, limiting their use for valuable surface finishes with a detailed texture. Not all surface treatments are compatible with previously applied surface treatments, requiring their removal (Hurley, 2011). The effects of the removal of previous surface treatments can be superficial in case of coatings, or require more in depth material removal in case the pores are covered or filled.

Surface treatments can fail pre-maturely, or may last longer than initially expected. In general, their durability is affected by weathering and by the risk of debonding due to entrapped water vapour (Bertolini et al., 2004; Nijland, Lubelli, van Hees & de Richemont, 2009; Van Hees, 1998). Surface treatments can be negatively affected by present damage symptoms such as cracks. Specially active cracks must be considered when applying, as the coating might not be flexible enough to bridge them and compensate the movement on the long-term (Figure 9.23). Premature failure is often caused by ingress of moisture, a poor surface treatment, and application problems. Figure 9.24 shows an example of a failed repair with a cementitious coating applied on a plain concrete structure with ASR (Bakker, 1996), where the moisture source was not eliminated (e.g. thickness of the walls in combination with moisture content, ingress through the rear of the earth retaining walls). Other external factors which destroy the effectiveness of coatings such as drilled holes or later repairs which were not coated must be considered as well. In case the repair fails, degradation mechanisms such as corrosion can propagate again.

The durability of surface treatments is assumed to be between 3 to 10 years (Hurley, 2011); tests confirm a durability of 5 years (Bertolini et al., 2004; Polder et al., 2001). In practice, a longer service life of up to 30 years has been observed (for brick masonry) (Van Hees, 1998). Therefore, options for retreatability during several intervention cycles is relevant (retreatability of hydrophobic impregnation is considered possible) (Nijland et al., 2009; Van Hees, 1998).

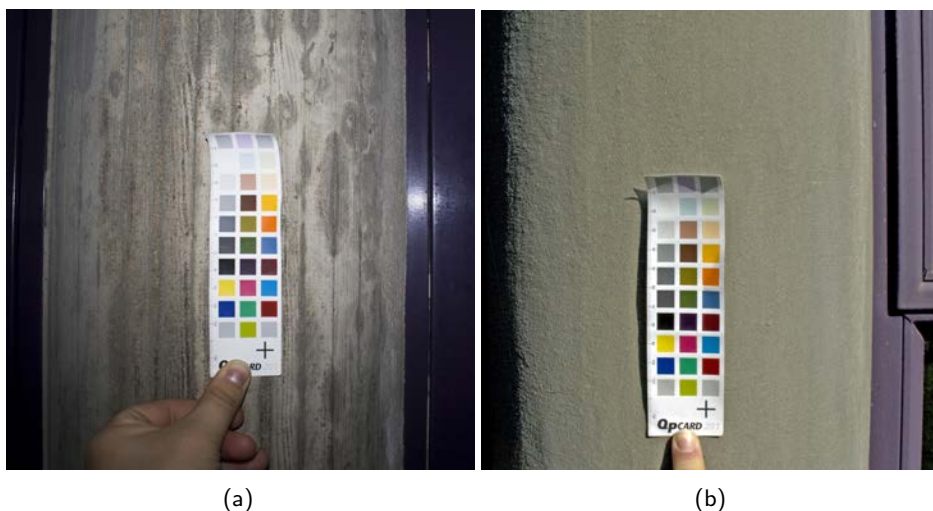


Figure 9.19 Comparison of two concrete surfaces (former orphanage, Amsterdam, A. van Eyck, 1959-61, situation 2008). a) Interior side of a column with the original surface colour and texture of wooden formwork imprints. b) Exterior side after surface treatment, changing colour and texture.



Figure 9.20 Example of a grey painted, previously exposed, concrete surface; the original more brownish colour and colour variations due to visible aggregates cannot be experienced anymore (Olympic stadium, Amsterdam, J. Wils, 1928, situation 2008).



Figure 9.21 Example of the colour change caused by surface treatments: the original composition of the prefabricated balustrades is white Portland cement with Rhine gravel, claustra in the middle of the balustrade made with white gravel and sand blasted (Schelling, 1952b); the architect explicitly rejected painting of concrete (Train station Hengelo, H.G.J. Schelling, 1952, situation 2009).



Figure 9.22 Example of the visual impact of anti-graffiti coatings: the lower zone of the façade was treated and is clearly distinguishable from the untreated upper zone (Former tax office, Amsterdam, G. Friedhoff and M. Bolten, 1954–1958, situation 2011).

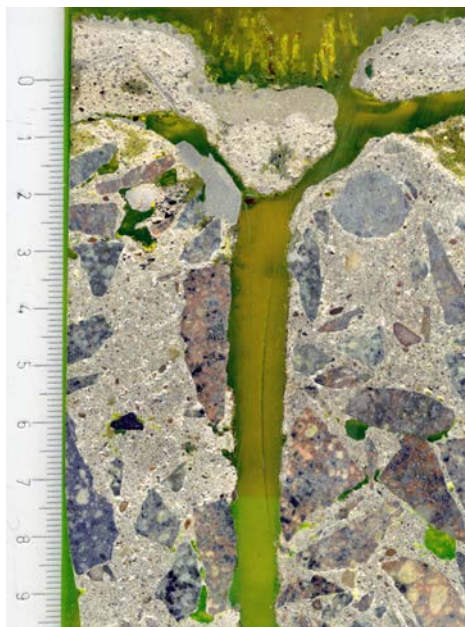


Figure 9.23 Section through a core showing a failed repair (concrete overlay) over a wide crack, the concrete is a plain concrete with crushed rock as coarse aggregate (plain concrete fort dating from 1895).

The best beneficial effects of coatings are reached when they are applied preventively, for example in the initiation phase in the case of corrosion risk. In a conservation context, the propagation phase has often already been reached, and the desired remaining service life of the historic structure is usually longer than a few decades, questioning but not excluding their suitability for conservation. Suitable situations could be for example the extension of the period the historic concrete could remain on-site by slowing down degradation and postponing its replacement.



(a)



(b)



(c)

Figure 9.24 Example of a failure of a coating due to the presence of moisture on a plain concrete fort (Fort near Aalsmeer, 1904, repair 1996, situation 2006). a) Overview b) Blistering of coating. c) Cracked coating with deposits indicating seepage.

9.4.5 Electrochemical repair techniques

Whereas the presence of the reinforcement is one of the main degradation risks for reinforced concrete due to corrosion, one can take advantage of its presence to treat corrosion. The underlying principle is that corrosion is an electrochemical process; electrical currents are applied to the reinforcement and interfere with the on-going degradation process. The intervention can either be a permanent installation with two subgroups: impressed current cathodic protection (ICCP) and galvanic cathodic protection; or temporary such as chloride extraction and re-alkalisation. Apart from the latter type, electrochemical repair techniques are mainly applied in cases of chloride attack, as conventional repairs are more troublesome (less durable) due to the incipient anode effect (see Section 9.4.2).

Other considered advantages of electrochemical repair methods are treatment of larger areas, requiring less concrete removal and lower costs than conventional repair; technical limitations are the use for pre-stressing steel, lacking electrical conductivity of the reinforcement, and the presence of epoxy coatings and epoxy injections (Broomfield, 2007). The main advantage for historic concrete is the fact that less original material has to be removed, and thereby allows the preservation of more original material. In addition, electrochemical techniques are almost reversible, and retreatable. The limited electrical continuity of some historic reinforcement systems is, however, sometimes expressed as an obstacle. The concern is that too many zones are required, making its use too expensive, and the danger of stray currents causing locally accelerated corrosion due to lacking conductivity.

To pre-evaluate the suitability of a historic reinforcement system for the application of an electrochemical repair technique, a preliminary study of the reinforcement system and the method of connection is advisable. In Chapter 6 *Reinforcement*, it was shown, that several reinforcement systems were applied for historic concrete. The techniques to connect the individual reinforcement bars varied during time, from no connection at all, to the use of wires or bolts, and welding (see Figure 2.16 Timeline reinforcement used for historic concrete). Some systems were originally connected, such as expended metal, or welded fabric.

A lack of conductivity does not exclude the use of electrochemical repair techniques as it is possible to achieve conductivity by connecting the individual reinforcement members afterwards, for example by welding with a compatible ferrous metal, which can be tested with trial mock-ups (Atkins, Lambert & Coull, 2002; Drewett & Bott, 2011). It has to be carefully evaluated whether individual metal elements, either from the reinforcement or from other elements, have to be connected to the cathodic system if they are not at risk of corrosion and can be insulated (Drewett & Bott, 2011).

Compared to the application of electrochemical methods on modern reinforcement systems, application on historic concrete structures might require more material loss because electrical conductivity often still has to be made. Nevertheless, the material loss might be smaller than applying a conventional repair. The material loss of historic concrete should be kept in mind and compared with the material

loss when applying conventional repair techniques, whilst considering the conservation aim and the ascribed heritage values to the materials. However, advantage can be taken of situations where the reinforcement is once exposed during large-scale interventions (see for example Figure 9.6). It might be considered whether installing preventively conductivity of the reinforcement might be beneficial, depending on the value of the historic reinforcement and the remaining corrosion risk after repair, and thereby facilitate the future application of electrochemical repair techniques.

9.4.5.1 Cathodic protection

Cathodic protection (CP) is the most wide-spread electrochemical repair technique for concrete (see also CUR recommendation 45, 1996; NEN-EN-ISO 12696:2012 Cathodic protection of steel in concrete). This technique has been used in the United States of America since about 1975 and in Europe since about 1984; in the Netherlands, cathodic protection has been used since 1987, initially mainly for buildings (Polder, Worm, Courage & Leegwater, 2011). Since then, the technique has matured and its use increased, replacing more traditional repairs of corrosion damaged concrete, and has been applied on cathodic protection in over 150 structures in the Netherlands (Polder & Leegwater, 2012).

Cathodic protection does not modify the properties of the concrete to prevent corrosion (for example pH value, chloride content), but intervenes in the corrosion process in such a way that during electrical chemical processes the reinforcement will not be consumed. It is out of the scope of this thesis to discuss the details of cathodic protection and many references exist which explain the underlying electrochemical processes (for example Bertolini et al., 2004; Broomfield, 2007). Instead, after a short explanation of the underlying principle, the benefits and risks will be discussed.

During corrosion of the reinforcement steel, two zones are formed on the steel: an anodic zone and a cathodic zone. At the anode, the steel is dissolved, releasing electrons which pass through the steel to the cathode, with the following anodic reaction:



At the cathode the steel itself is not affected and the electrons are consumed with oxygen and water, with the following cathodic reaction:



The principle of cathodic protection is to change the anode on the steel into a cathode by introducing a new anode. By moving the anodic reaction outside of the reinforcement, the reinforcement steel will not be consumed anymore and thereby protected. This can be done by using an external source which delivers the required electrons for the cathodic reaction.

Two principles of cathodic protection exist: first, applying an impressed current to the reinforcement, known as impressed current cathodic protection (ICCP); second, connecting the reinforcement with a less noble metal which functions as an anode and dissolves instead of the reinforcement. The latter uses the principles of galvanic corrosion, therefore this technique is referred to as galvanic cathodic protection, sacrificial cathodic protection, or a passive system.

In case of an **impressed current cathodic protection (ICCP)**, a new anode is either placed on the concrete in the form of mesh, strips or coating, or embedded into the concrete (Figure 9.25). An electrical conductive connection with the reinforcement is necessary and the pore water in the concrete functions as electrolyte. An external electrical current is applied, which supplies the required electrons and hereby decreases the corrosion rate as no more electrons are consumed from the reinforcement steel. This technique involves regular monitoring of the effectiveness of the system. The setup requires several components, such as the anode itself, connections between the anode and cathode, and power source, and monitoring systems.

The other option is **galvanic cathodic protection** where a less noble metal (for example zinc) is connected to the reinforcement which will function as an anode and sacrifice itself by corroding. This technique does not require an external electrical source. Traditional sacrificial anode systems are coatings or meshes applied on the surface, whereas lately systems are discussed where the sacrificial anode is embedded into a repair mortar in the concrete next to the reinforcement (Figure 9.25). The durability of galvanic cathodic protection with an embedded anode is estimated between 10 and 20 years, extrapolations of more recent anode types indicate even a service life between 24 and 37 years (Sergi, 2010, 2011).

The appearance of the concrete will be affected by the cathodic protection system applied. The dimensions of the impact, however, vary with the chosen anode system (Figure 9.25). The entire original concrete surface will be covered with a system using meshes or coatings. Some surfaces, such as painted or plastered surfaces, can be reconstructed (see Section 9.4.2). For the reconstruction of tooled surface finishes, it should be investigated with trials whether tooling would be possible, and not affect the bond between sprayed concrete, anode and parent concrete.

Although covered, the original surface would be still in-situ and in theory still function as a carrier of historical information. However, the surface can be slightly damaged as it might be roughened to apply the sprayed concrete or when later removing the anodic system (for example grit blasting of the overlay). Another consideration is that present damage, such as spalled concrete, delamination and cracks should be treated to ensure the conductivity of the concrete. Hereby, the same considerations as for repair mortars are applicable, and it is required that the repair material is electrically conductive.

Systems where the anode is embedded into the concrete leave more of the original surface intact and visible, as only locally small holes have to be drilled to insert the anode (Figure 9.25). To close the holes, either the original surface

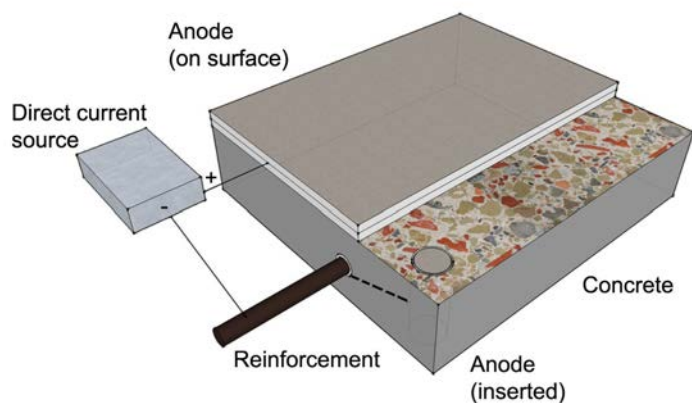


Figure 9.25 Schematic drawing of the setup of two different anode types and their impact on the historic concrete: in case the anode (mesh covered with a cement overlay) is placed on the surface, the original surface is covered; local connection to the reinforcement is necessary. In case of inserted anodes, most of the original surface can remain unaltered and visible; only to insert the anode and to enable the connection between anode and reinforcement, the concrete needs to be removed.

saved from the taken core can be applied or the original textured and colour of the concrete restored. When placing these anode systems, a balance has to be found between technically correct locations for access to the reinforcement and the zoning of the cathodic protection system, and the unobtrusive appearance of the local surface repairs necessary when placing the anodes.

Studies have been carried out on the failure methods of cathodic protection systems (Polder & Peelen, 2011), and different causes can be identified such as the degradation of the anode material itself, failure of reference electrodes and of anode-copper connections. The side effect of such failures is that corrosion can propagate again, usually after quite some time. A replacement of failed components is possible.

9.4.5.2 Electrochemical realkalisation

One of the causes of reinforcement corrosion is the carbonation of concrete. In the alkaline environment with a pH value > 12.5 of non-carbonated concrete, the reinforcement is protected by the formation of a passivity layer of ferrous oxides on the surface of the reinforcement. During carbonation, the pH value in the pore solution of the concrete decreases below 10; the passivity layer is destroyed, and corrosion can be induced, given that sufficient moisture and oxygen is available. The concept behind realkalisation is to increase the pH value of the concrete near the reinforcement by means of introducing an alkaline solution into the con-

crete and by generating hydroxyl ions (OH^-) at the cathode, i.e. reinforcement bar (Schneck, 2011; Tong, Bouteiller, Marie-Victoire & Joiret, 2011).

Electrochemical realkalisation is defined as an *“electrochemical treatment for restoring to concrete, which surrounds reinforcing bars, a high pH value corresponding to sound, non-carbonated concrete”* (CEN/TS 14038-1:2004). It is carried out by applying an anode on the concrete surface, for example a steel or titanium mesh which is connected to the reinforcement. The anode is inserted in an electrolyte, for instance sodium carbonate solution, potassium carbonate solution or water, and a current is applied. The electrolyte can be applied to paper pulp which is sprayed on the anode, or the liquid electrolyte is placed in a shutter which is placed against the concrete (Grantham, 2011c).

As preparation works, unsound concrete should be removed (e.g. delaminated, honeycombed) and repair material with an *“unacceptably high electrical resistivity (>200% of parent company resistivity) and/or containing any other materials that may impair the effects of realkalization shall be broken out to achieve a clean, physically sound concrete surface”* (CEN/TS 14038-1:2004). In case the reinforcement is not continuous, local access to the reinforcement to install continuity is necessary. For electrochemical realkalisation and electrochemical chloride extraction (Section 9.4.5.3), the electrical continuity is considered more relevant than for cathodic protection as higher charge densities are applied, increasing the risk of corrosion of isolated reinforcement bars; however not many cases have been reported where this side-effect occurred (Broomfield, 2007).

The advantages for its application on historic concrete structures is that it is a temporary installation and requires less material loss than conventional repair methods; it does not demand a change of the geometry of the concrete member, for example by increasing the thickness of the concrete cover. In general, its application is advised before the concrete has spalled, but it has been applied after spalling has occurred, using the exposed reinforcement as access points to connect the realkalisation system (Bertolini et al., 2008). In the Netherlands, trials have been made with realkalisation (Van den Hondel, Borsje, Rijnen & Winkelman, 1999), but the technique has not been widely applied.

The efficiency of electrochemical realkalisation, its measurement and its durability is still discussed. What can be concluded is that it at least slows down temporally the corrosion process (Tong et al., 2011) and indications exist that the treatment can last up to 10 years (Sergi, 2010). The factors influencing the effectiveness, such as the composition of the concrete, are not totally understood yet either (Redaelli & Bertolini, 2011), and should be taken into account when applying this technique for historic concrete as the composition of the historic concrete can differ from modern concrete. According to Redaelli & Bertolini (2011), concretes with a positive effect had a high w/c ratio of 0.7, as the resulting higher permeability allowed a better ingress of the alkaline solution; the presence of chlorides reduced the effectiveness. The treatment is more effective for concretes made with Portland cement than those made with fly ash or slag cement (Bertolini et al., 2004). As Portland cement was the main binder used for historic concrete struc-

tures, and as the w/c ratio was commonly above 0,6 (see Section 5.3.2 *Quantity of mixing water*), increases the potential of using such techniques effectively for historic concrete buildings.

Concerning the side-effects of electrochemical realkalisation, the impact on the cement matrix and the corrosion rate are under discussion. Further studies are needed to obtain more information of the influence of this treatment, such as on the corrosion rate. Lab tests show that this treatment in fact can increase the corrosion rate, especially if the reinforcement shows already signs of corrosion before treatment, whereas from the field this phenomenon has not been observed (Bertolini et al., 2011). Indications are given that the cement matrix changes such as a reduction of the permeability and porosity, and increase of strength (Grantham, 2011c). Although no cases have been reported, the risks exist of provoking an alkali-aggregate reaction in case alkali sensitive aggregates are present and new alkalis are introduced (CEN/TS 14038-1:2004). The used electrolyte can affect the concrete as well, e.g. sodium carbonate electrolyte influences the adhesion of coatings and can cause a short-term efflorescence; if water is used, chlorides present can be transformed into chlorine (Grantham, 2011c). The removal of the pulp applied on the concrete surface should be done carefully in case the historic concrete surface is valuable. Small scale local damage will be involved for the fixing of the components of the re-alkalisation system.

Case studies of the realkalisation of some historic concrete structures dating from the 1920s to 1960s have been published, showing that its application is possible for historic concrete (Bertolini et al., 2008; De Jonge, 1997). Compared to the standard treatment of damage due to carbonation induced corrosion - patch repair with removal of the carbonated concrete - realkalisation is even discussed as more appropriate to fulfil the demands of heritage care. Arguments supporting realkalisation are that it requires less material removal, and the limited material loss to connect the reinforcement with the anode can be considered justifiable (Bertolini et al., 2008).

9.4.5.3 Electrochemical chloride extraction (ECE)

The treatment of corrosion due to chloride attack can either be done by interfering with the corrosion process, as in the case of cathodic protection, or by removing the chlorides from the concrete. This method restores long-term corrosion protection of the reinforcement, known as electrochemical chloride extraction (ECE)² (CEN/TS 14038-2:2011). Electrochemical chloride extraction reduces the chloride content by removing dissolved chloride ions from the concrete due to an externally applied electrical field (Schneck, 2011).

The technique is similar to electrochemical realkalisation (see Section 9.4.5.2) and increases the alkalinity of the concrete as hydroxyl ions (OH^-) are formed at the cathode. The set-up involves an electrolyte, an anode and an electrical source.

²Synonyms: chloride removal, desalination.

Titanium wire meshes or reinforcing steel meshes can be used as anodes; water or saturated calcium hydroxide solutions as electrolyte. The electrolyte can be applied through a paste sprayed on the concrete or as a liquid in tanks. More recent developments are to use a sacrificial anode (Bertolini et al., 2004).

To achieve conductivity, unsound concrete has to be removed or repaired (e.g. delamination, cracks, honeycombing, poor construction joints) as otherwise it could prevent *“flow and thereby impair the effectiveness of the chloride extraction treatment”* and previous repairs should be identified and evaluated for their electrical resistivity (CEN/TS 14038-2:2011).

The origin of the chlorides has an influence of the efficiency of the treatment. Chloride which penetrated into the concrete can be removed more efficiently than chlorides which were mixed in (Schneck, 2011). The possible quantity of removable chlorides is assumed to be between 50% and 90% (Bertolini et al., 2004), and cannot be reduced to a chloride content of 0%; however, a chloride content of 0.4% is considered acceptable (CEN/TS 14038-2:2011). The distribution of the chloride content after treatment is not homogenous; the content is lower near the reinforcement and therefore the spacing between the individual reinforcement members should be considered when evaluating the effectiveness of the treatment. When working with historic concrete it should be remembered that the placing of the reinforcement can deviate from modern reinforcement layouts, and reinforcement bars could have moved during execution.

The efficiency of electrochemical chloride extraction is influenced by the binder type and is considered more efficient when Portland cement was used than for binders with slag substitutes (Abdelaziz, Abdelalim & Fawzy, 2009; Andrade, Martínez, Castellote & García De Viedma, 2009). However, other tests showed that there was no difference between using Portland cement or blast furnace slag cement (Polder, 1996). The durability of effects of the chloride extraction and the prevention of further corrosion are influenced by the remaining presence of the chloride source. If present, the chloride content could increase again in the future. Not sufficient data exists yet on the durability of the intervention (Broomfield, 2007).

The side-effects are similar to those for electrochemical realkalisation (Section 9.4.5.2). Caution has to be given that *“some electrolyte materials may change the surface appearance of the concrete”* (CEN/TS 14038-2:2011). Acid etching of the surface may occur with longer treatments an/or higher current densities. Discussions exist whether the treatment negatively affects the bond strength between reinforcement bar and concrete. For smooth reinforcement bars, this could have more consequences than for ribbed reinforcement bars (Bertolini et al., 2004; Schneck, 2011); this should be considered, as most reinforcement bars used in historic concrete in the Netherlands have a smooth surface and a round profile (see Section 6.3 *Geometry of reinforcement bars*). Evidence of the application of this technique for historic concrete and in a conservation context could not be found; the technique has been applied for concrete bridges in a standard repair setting, for example in the United States of America and Germany (Schneck, 2011).



(a)



(b)



(c)

Figure 9.26 Example of external strengthening with an additional reinforced concrete layer on an existing roof slab (Dresselhuys pavilion, Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928, situation 2008). a) Picture of the reinforcement on top of the existing slab; b,c) after completion of works.

9.4.6 External strengthening

Although structural issues related to historic concrete are not further discussed in the thesis, methods to structurally strengthen the concrete will be shortly addressed. These should be designed on a structural basis. An improvement of the structural capacity can be part of an intervention approach to guarantee functionality, an important demand for the built heritage. If the structural performance of the (reinforced) concrete is too little or endangered, it is possible to re-strengthen the concrete by applying an external load bearing material. Three main concepts exist: the attachment of external steel plates, applying a concrete overlay (both methods increasing the dead-load of the structure), or by applying composites, such as (carbon) fibre reinforced polymers (FRP) (CUR recommendation 91, 2007; Russell, 2011).

For all methods, the material is attached to the surface; it thereby changes its appearance, either totally or locally if only strips are used. Modifying the resulting surface colour and texture is partially possible. For concrete overlays, the same options exist as for sprayed concrete (see Section 9.4.2). FRP can be covered with a thin mortar layer, which can be adapted, to a certain limit, in colour and texture. The main advantage of external strengthening methods is that the original historic material, although covered, can stay in-situ, limited damage occurs in the original material and the functionality of a monument is restored. Whereas the attachment of steel plates and additional concrete overlays significantly modify the proportions of the concrete member (Figure 9.26), FRP is characterised by minor geometrical changes, which are only a few mm thick (Figure 9.27).

The side-effects are mainly related to the changes in the permeability of the concrete surface. For FRP, the low permeability is caused by using an epoxy resin to attach the FRP with the risks of entrapped moisture, which can lead to freeze-thaw damage or debonding (Blanksvärd, Täljsten & Carolin, 2009). Another risk is the behaviour of the FRP when exposed to high temperatures (e.g. fire) as the strength can be reduced, however, the capacity is still considered higher than in case no FRP would have been applied (Ahmed & Kodur, 2011).

9.5 Conclusion

In this chapter it was shown that differences exist between the field of concrete conservation and concrete repair, and that it is relevant to understand these differences. A main aspect is that the aims differ; conservation requires additionally the preservation of heritage values, respect towards the historic fabric and consideration of a perpetual heritage service life. A stronger emphasis on conceptual demands such as compatibility, retreatability and durability is therefore necessary. Concerning the conceptual demands, more research is required to have better background information to choose appropriate repair techniques and to fully

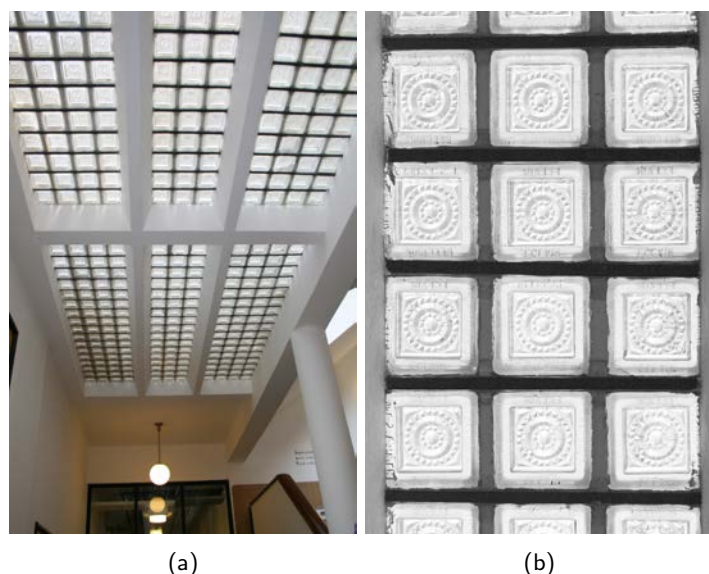


Figure 9.27 Example of FRP used to strengthen a glass brick floor (Vocational school (Ambachtsschool), Zwolle, A. Baart & L. Krook, 1934, situation 2011). a) Overview soffit. b) Close-up showing horizontal joints covered with strips and vertical joints showing original mortar.

understand the long-time benefits and risks. Above all, a new repair strategy is needed, considering the requirements of conservation.

The compatibility of old and new is essential for the success of an intervention, requiring an understanding of the original material, cause of damage, repair material, and of the boundary conditions. It was shown that no such thing as a universal and everlasting repair exists. Depending on the chosen technique and underlying cause of damage, interventions might be necessary every few years up to a few decades. A rethinking of the way techniques are chosen, namely only for the near future, to a thinking ahead for a strategy for several intervention cycles is necessary with regard to the increased heritage service life. This includes an evaluation of the compatibility of different repair techniques which might be applied in the different repair cycles. In practice, because several repair cycles will occur, it is necessary to implement a good documentation of the chosen repair materials, underlying damage and conservation aim. This would facilitate the planning of the next intervention cycle.

Caution has to be given when a technique is rather recent and little track records exist on its behaviour in the field, especially as limited experience exists with its use for historic concrete. Although in conservation practice there is a tendency to use traditional techniques (e.g. repair mortars), the use of new, experimental techniques (e.g. realkalisation) is not excluded for conservation but it is required

that “*the efficacy of which has been shown by scientific data and proved by experience*” (ICOMOS 1964, art. 10). Newly developed repair techniques should be reviewed for their potential for conservation and compatibility with historic concrete. For example, current research to prevent or inhibit ASR with lithium-based admixtures seems promising when added to fresh concrete; their usability for existing structures still needs more research (Bertolini et al., 2011). Another aspect is the evaluation of the impact of the repair technique on the historic material and on the heritage values. To be able to do so, it is necessary to understand the heritage values and their relationship with the historic fabric, and judge whether a proposed intervention is beneficial.

In conservation practice it is necessary to clearly outline the demands towards a repair and to determine which aspects differ from a normal concrete repair. This includes, for example, the composition, colour and texture of repair mortars, the degree of concrete removal or the method of surface cleaning. Trials which should already be carried out in the planning phase can be crucial to evaluate and compare proposed techniques on the impact on the original material and heritage values and its appearance. It should be judged whether it treats either symptoms or cause of damage.

It is not impossible to modify a repair technique to match closer the conservation demands but it requires a clear description of what is desired and understanding of what is possible. A common critique is the reliance on proprietary repair mortars (Macdonald, 2003). The development within the field of conservation of bedding and pointing mortar shows that a transition to more tailored repair materials is possible, but it requires detailed material research for a suitable mix design and trials for each project. More compatible mortars, designed considering both conservation aspects and technical requirements, can be achieved, leading to better results on the long-term (see for example Schueremans et al., 2011; van Balen et al., 2005, 2003; Velosa et al., 2010).

Reviewing available repair techniques, their impact on the heritage values vary. It not only depends on the repair technique itself, but also on the type of heritage value and historic concrete. In general, heritage values related to the surface of historic concrete are more affected by repairs, as they either cover the surface (e.g. coatings) or locally disturb the appearance (e.g. patch repairs). Preparatory works such as cleaning of a surface can destroy signs of ageing (e.g. biological growth) or diminish textural details of a surface. Yet, for these cases, awareness is lately increasing and possibilities to reduce the impact investigated (e.g. modification of repair mortars).

Less attention is paid to the impact of repairs on the concrete bulk and the reinforcement. Causes are that to identify heritage values related to these material aspects (e.g. technological development) require more background knowledge, and that the impact is less visible after completion of works. In addition, the removal of concrete is often justified, as the quality is less than modern concrete, and options for its preservation not investigated (e.g. injections).

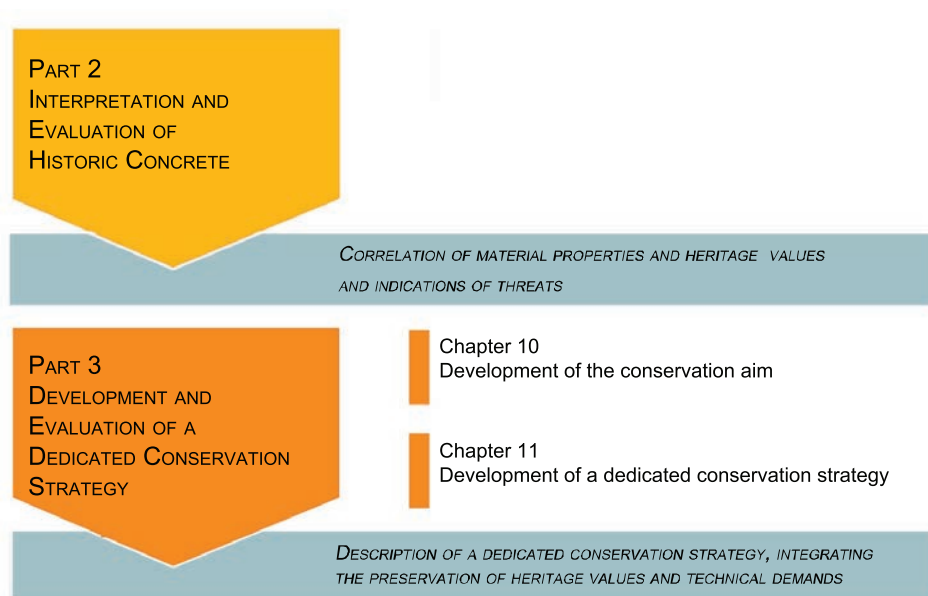
Too little attention is still given during the planning phase on possible altern-

atives, including no intervention at all, and the focus is on treating a causes and symptoms of damages, instead of discussing first a conservation strategy.

With this chapter, Part II of this thesis concludes. In the following Part III, the gained insight from Parts I and II will be combined to develop a dedicated conservation strategy.

Part III

Development and Evaluation of a Dedicated Conservation Strategy



Part outline

In the process of developing a dedicated conservation strategy, the required background information has been gathered and described in the previous chapters. In Part I *Understanding and Characterisation of Historic Concrete*, information was given on historic concrete in the Netherlands, allowing an understanding and characterisation of historic concrete. In Part II *Interpretation and Evaluation of Historic Concrete*, the actual state of the historic concrete was discussed and methods introduced to identify the correlation between the heritage values, historic concrete and state of conservation. Concrete repair techniques were reviewed for their risks and benefits. With this knowledge, from a conservation point of view, preliminary conclusions can be drawn on whether an intervention is necessary.

In Part III, methods to develop a dedicated conservation strategy will be introduced. In Chapter 10 *Development of the conservation aim*, an approach is suggested to identify the boundary conditions and aim of a conservation strategy. Hereby, criteria are based on both, preservation of heritage values and technical demands.

New steps are introduced; first, four different states of the historic concrete are defined. A comparison of the different states and an analysis of their relationship enables to formulate monument specific criteria for a dedicated conservation strategy. In the concluding Chapter 11 *Development of a dedicated conservation strategy*, the four states are used again in order to develop and evaluate a dedicated conservation strategy.

Chapter 10

Development of the conservation aim

Chapter Outline

In the process of developing and evaluating a dedicated conservation strategy, it is in the first place necessary to formulate a conservation aim. In this chapter, it will be discussed why a conservation aim is necessary and how it can discharge discussions from unnecessary obstacles. Thereby, it gives guidance when formulating the requirements of a conservation strategy. A new approach is introduced to develop the conservation aim, based on four different (conceptual) states of the historic concrete for both technical performance and heritage values. By analysing the different states, the need and requirements of an intervention can be formulated in order to reach the conservation aim. The three cases introduced in Part II of the thesis will be used to illustrate the suggested approach.

10.1 Introduction

In Part II *Interpretation and Evaluation of Historic Concrete*, it was discussed that the preservation of heritage values and of the original material are a main aim of conservation, together with slowing down degradation. However, the question is how to apply such general aims, combining technical and conceptual aspects for a specific conservation project.

In practice, straightforward solutions that allow the preservation of all heritage values whilst fully dealing with all degradation causes and symptoms, are seldom possible. In addition, it is quite common to distinguish between questions related to the treatment of degradation and those related to the preservation of heritage values. Based on the encountered deterioration, interventions are suggested which would treat the cause of damage and/or damage symptoms. The underlying questions usually refer to technical aspects, and solutions are constrained by

costs, time and availability of the technique. Such an approach does not exclude a proper solution that would preserve the heritage values, but in general, their preservation is at risk as they are neither considered nor explicitly discussed.

A standardised list of conservation techniques to be used for each combination of heritage values, type of historic concrete and encountered damage cannot be made, as the combinations are too manifold. However, the underlying question for all combinations is the same: in which state does the material best preserve the heritage values? The answers can vary from the current historic concrete's state of conservation to a modified state; the emphasis can either be placed on the original material or on the appearance of the building (which do not necessarily exclude each other). The conservation aim is a formulation of the state in which the historic concrete and the building or structure would preserve the heritage values the best. It should be based on an analysis of the previously gained information on the construction history and of the heritage values. The formulation of a conservation aim is *not* an academic mind game, but is a serious discussion of what to preserve before discussing how to do it.

To formulate the conservation aim, four different (conceptual) states of the historic material should be compared, for both technical performance and heritage values, which will be introduced and discussed in Section 10.2. By comparing the four different states, the need of intervention is indicated based on the preservation of heritage values, and technical and functional demands. The main advantage of such an approach is that discussions are not impeded by technical and financial questions related to the feasibility of a treatment; instead, discussions are initiated on what should be the ideal state of the object and hereby deliver criteria, which are fine-tuned for the monument in question.

It is not a prerequisite that the chosen conservation aim is technically or economically feasible. Its main purpose is to function as a point of orientation when discussing and evaluating different conservation strategies with respect to their impact on both heritage values and material. Practical obstacles not allowing to achieve the conservation aim might, for example, be a too poor state of conservation of the historic concrete, a (new) function required, time or financial limits, or no suitable repair technique available. Other dilemmas occur if technical demands and the preservation of heritage values contradict or even mutually exclude each other. In such cases, a previously formulated conservation aim can give guidance to find alternative solutions and to articulate advantages and disadvantages of different conservation strategies. The suggested approach will be illustrated by means of the cases previously introduced in Part II: Fort Bezuiden Spaarndam, the Hofplein railway viaduct and the earth retaining walls of the Groot Museum.

10.2 Four different states of the historic concrete

In this section, four different states of the historic concrete will be discussed:

- The actual state of conservation, i.e. the actual state as observed during inspection.
- The ideal state of conservation, mutually to be agreed on, which represent the (theoretical) best state of the historic concrete.
- The expected state of conservation, i.e. the theoretical state in which the historic concrete is supposed to be in the future without intervention.
- The acceptable state of conservation, which represents the minimum acceptable performance.

The differences between the actual and the expected state of conservation, and the ideal and the acceptable state of conservation, respectively, indicate the need of intervention, as either the historic material or the heritage values are endangered. Each of these states indicates criteria for the conservation aim. By analysing their mutual relationships, direction is given for defining the conservation aim.

10.2.1 Actual state of conservation

The starting point when determining the conservation aim is the actual state of conservation. In Part II of this thesis, the state of conservation was addressed in context with degradation and its correlation with heritage values. It reflects the alterations the material and building underwent since the day of construction, and is used for the interpretation of the building and the assessment of heritage values.

From technical surveys, conclusions can be drawn whether critical thresholds have been reached affecting the safety and usability of the structure and material. An analysis of the correlation between heritage values and the historic concrete gives information on whether the heritage values are endangered (see Chapter 8 *Mutual relationship between the heritage values, historic concrete and state of conservation*). The thresholds have to be mutually agreed on and will be further discussed in Section 10.2.4. As most monuments have a function, factors influencing the functionality should be reviewed as well in case they are related to or affect the historic material (e.g. load bearing capacity, seepages).

When determining and documenting the actual state of conservation, differences with previous phases of the building and their cause should be identified as well. This can give guidance when later discussing the ideal state. Examples are the type and scale of interventions (e.g. transformations or local repairs), causes of damage (material intrinsic or external events) or functional changes resulting in neglect, modifications or repair. Information on the reversibility of previous interventions should be given, as it can facilitate later discussions on the feasibility of the conservation aim. As will be shown below, some researchers in the field of conservation philosophy consider the actual state of conservation conceptually as the ideal state of a monument as it supposedly reflects best the history of a building.

10.2.2 Ideal state

The ideal state of a monument has always been subject of discussion within the field of conservation. Much has been written on the different conservation philosophies expressing the ideal state of a monument in a conceptual way (for example Earl, 2003; Jokilehto, 2002; Stanley Price, Talley Jr. & Vaccaro, 1996). Most known are the oppositional approaches of the French Eugène Emmanuel Viollet-le-Duc (1814-1879), and the British John Ruskin (1819-1900) and William Morris (1834-1896). Viollet-le-Duc is known for his concept to restore monuments into a state, which would be in style of the original. This included the removal of later attributions and introduction of new elements, which would not necessarily result in the original state based on evidence but on a study of the object and interpretation of what could have been the ideal state. This allowed stylistic improvements. Ruskin and Morris are often named in context of anti-restoration, an opposing movement towards ideas such as those of Viollet-le-Duc. In this view, the actual state was considered the ideal state of conservation, including the idealisation of ruins, and should be preserved.

The work of the architect Petrus Josephus Hubertus (Pierre) Cuypers (1827-1921) can be seen as Dutch example for the application of the ideas of Viollet-le-Duc. During the last two centuries, reconstructions were commonly carried out in the Netherlands; still intact monuments were brought back to an (assumed) previous state, often associated with historically glorious periods (Denslagen, 1994).

On an architectural and stylistic scale, the actual state of conservation is still often considered as the ideal state, although under special circumstances a removal of later additions can be justified. In article 11 of the Charter of Venice it is demanded that *“the valid contributions of all periods to the building of a monument must be respected, since unity of style is not the aim of a restoration. When a building includes the superimposed work of different periods, the revealing of the underlying state can only be justified in exceptional circumstances and when what is removed is of little interest and the material which is brought to light is of great historical, archaeological or aesthetic value, and its state of preservation good enough to justify the action. Evaluation of the importance of the elements involved and the decision as to what may be destroyed cannot rest solely on the individual in charge of the work.”* (ICOMOS, 1964).

Modifications of monuments to a known, earlier or assumed better state, i.e. reconstruction, have always been heavily discussed, and sometimes even considered as falsification (Denslagen, 2011). The returning of a monument into an original state is seen as an *“abstract idea”*; the original material and building have aged over time, creating a historical contradiction as the material is not identical to the original state anymore (Philippot, 1996, p. 273). Nevertheless, in practice, partial or complete reconstructions are not unknown (see Section 9.2.2). Reconstructions are commonly justified after warfare (James, 2006; Makaš, 2012).

Whereas the previous discussions are mainly stylistic and carried out on the scale of the monument, the question arises in which state the material should be

kept. An uncritical demand to preserve previous contributions can be noticed in practice for small-scale interventions, such as local repairs, which were often not carried out during a conservation campaign but as part of normal repair and maintenance. In Part II of this thesis, examples have been shown of the impact of different repair techniques on the historic concrete, especially their impact on the appearance of a monument. Often, a critical discussion whether the repair itself did not cause a stronger negative impact on the heritage values is not carried out. For example, many early exposed concrete buildings have successively been painted, often to cover up poor repairs. The variety in colour and texture of such buildings has been forgotten. Many buildings are not capable anymore to tell the story of the aesthetical development of concrete surfaces, supporting the prejudice of grey and dull concrete. Such buildings might tell a different story when the original surface would be exposed and aesthetically poor repairs replaced.

The question is when a previous intervention is part of the history and of the heritage values, or can be considered a minor intervention. For the latter case, the monument might gain more from its removal than from its preservation. Answers can be found when reviewing the history of the building, understanding the correlation between material properties, heritage values, and the underlying reasons for observed changes (for example ordinary maintenance, historic events, functional changes). With these references, it can be discussed in which state both building and material would represent the heritage values the best and would be able to transmit them for present and future generations (Appelbaum, 2009; Earl, 2003). For the field of art conservation, methods to determine the ideal state have been suggested. They are based on a review of the history and changes of an object for the relevance of the heritage values and to determine historically important events which caused in the past changes; the ideal state is used as guidance when planning a realistic treatment goal (Appelbaum, 2009). For buildings and structures, the demand of functionality, both extent and type, has to be considered as well when deciding on an ideal state.

The influence of the different conceptual interpretations of the ideal state can be seen in practice. When the ideal state should reflect the intention of the architect, a modification into the state after completing construction works is often aimed for (Figure 1.5); when the ideal state should enable to transmit the lifetime of a building, traces of use and erosion and soiling can be considered relevant (for example Hinterthür, 1997), when the historic concrete should testify for a historic event, the ideal state could result in the desire to preserve local damage (Van Hunen, 2006, Figure 8.11).

10.2.3 Expected state of conservation

Whereas the ideal state is conceptual, the expected state of conservation reflects the state the historic concrete would be in without intervention after a certain period. In order to describe objectively the expected state of conservation, it is necessary that a detailed assessment of the present state of conservation is carried

out. This allows a prognosis on the propagation of damage, and the resulting effects on both historic material and heritage values. It is important to use the actual state of conservation without considering potential interventions as a starting point.

When predicting the expected state of conservation, both technical aspects and preservation of heritage values should be addressed. It should be understood that the expected state of conservation is time-dependent and predictive. The period to which the expected state of conservation refers should be between a realistic point in the future (for example a few decades) for which sufficient data are available to make a prediction, and an assumed point, reflecting the perpetual heritage service life (see Section 9.3.4 *Heritage service life*). The expected state of conservation is comparable with the outcome of the “do nothing” option (NEN-EN 1504-09:2008). When describing the expected state of conservation, the further development of present and possible future degradation should be indicated, including a prognosis on whether degradation will slow down, accelerate or remain unchanged with time. In an evaluation, the following aspects should be addressed: the safety of the structure and for users, the functionality, material loss and changes, and development of the heritage values.

A description of the expected state of conservation should include an assessment of the propagation of individual damage processes and the consequences for the heritage values, including their endangerment. Depending on the complexity of the material properties, degradation and importance of the original material, an appropriate level of detail should be used. Experience and comparison with similar objects can give first indications. For more complex situations, for example uncommon material properties or higher risks for material and heritage values, a more detailed analysis of the expected state might be necessary.

An advantage for concrete conservation is that it can benefit from existing models for prediction of material behaviour. In context of the durability of civil infrastructure, models and probabilistic approaches for the behaviour of concrete during time have been developed, mainly considering the risk of corrosion (see for example DuraCrete R17, 2000; van Breugel, Ye & Yuan, 2010; The European Union - Brite Euram III, 1998, 2000). For concrete conservation, an adapted use of such approaches is possible although the deviating conceptual and material parameters have to be considered. For example, most models use material parameters obtained from modern concrete, which can significantly deviate from historic concrete, requiring further material research to obtain useable parameters.

The expected state of conservation can be used as reference point for two aspects: first, it can indicate when the expected state of conservation would be below an acceptable state of conservation, indicating the (future) need of intervention; second, it can be used as one of the reference points to evaluate the usefulness of alternative conservation strategies.

10.2.4 Acceptable state of conservation

The acceptable state of conservation is a mutually agreed minimum performance for ascribed heritage values, technical performance and functionality of the monument. If the state of conservation is near or below this state, the historic concrete, the ascribed heritage values and/or the function are endangered. Criteria regarding the minimum performance of the historic concrete or thresholds should be mutually agreed on and described.

Common technical thresholds relate to safety and functionality. Those related to the safety of a structure or to the initiation of degradation are usually measurable, but can vary during time due to increased use or insight into durability. Examples are the critical chloride concentration, carbonation depth or remaining load bearing capacity. Criteria for the minimum performance of heritage values are, however, qualitative and not universal. This means that not in all cases an exact point can be given when heritage values would be endangered irrevocably. Instead, case specific descriptions have to be made of the acceptable impact of the degree and quality of future changes (i.e. damage and intervention). Even for the same monument, the thresholds can vary, depending on the importance of the element and the historic concrete. For example, criteria related to the appearance will be most likely higher for a representative façade than for an element, which will remain out of view. In addition, thresholds related to the heritage values might vary during time influenced by societal changes and new historic insight. Functional thresholds can vary with time as well due to functional changes.

10.2.5 Relationship between the four different states and conservation aim

In the previous sections, four different states of the historic concrete have been described, i.e. the actual, the ideal, the expected, and the acceptable states of conservation. From the actual and expected state of conservation, conclusions can be drawn on whether either the material or the heritage values are at risk and would require an intervention. Hereby, the thresholds developed for the acceptable state of conservation can be used to indicate if and when intervention is necessary. The ideal state describes the ambition of the intervention.

Understanding the relationship of the four different states of conservation gives information on both the need of conservation and the monument specific conservation aim. In Figure 10.1, the mutual relationships of different combinations of the states of conservation are illustrated. In an ideal situation, no intervention would be required as the actual state of conservation would be near the ideal state and would even remain so in the future (i.e. the expected state of conservation). In practice, it will most likely be that either the actual or the expected state of conservation is near one or more thresholds of the acceptable state of conservation (for example serious damage caused by corrosion, too high loss of original mater-

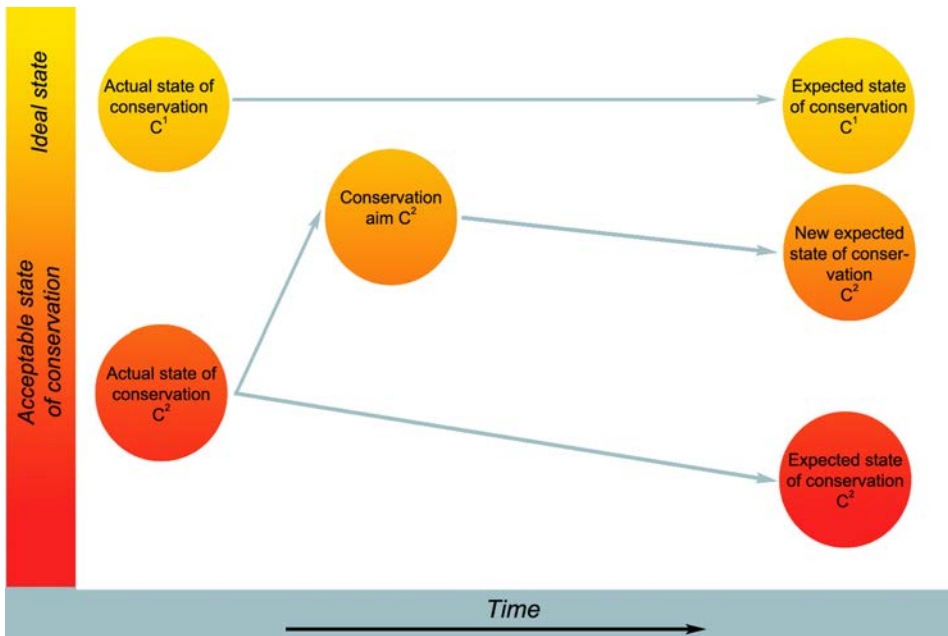


Figure 10.1 Example of the relationship of different states of the historic concrete. In an ideal situation, the state of conservation C^1 and the expected state of conservation C^1 would be near the ideal state, not requiring intervention. The state of conservation C^2 shows a more common situation, where both actual and the expected state of conservation are near or below the acceptable state: intervention is required, aiming at a state C^2 closer to the ideal state. The new expected state of conservation C^2 should be above the initial expected state of conservation.

ial), requiring an intervention to prevent further loss. The ideal state should be used as an orientation on the aspired results of the intervention.

In theory, guided by the conservation aim, a state closer to the ideal state than before intervention should be achieved. With the formulation of the conservation aim, a new reference point is created for the evaluation of the expected state of conservation. A prognosis should be made whether the new expected state of conservation will be superior to the expected state of conservation without intervention for a sufficiently long period. From comparing the different states of conservation, case-specific criteria for an intervention have to be formulated.

The conservation aim will be influenced by the threshold reached, for example, the expected loss of a valuable surface will require measures to prevent or to reduce the impact of the loss (e.g. local reconstruction). The gained insight from comparing the four different states will be used in the next step when developing a dedicated conservation strategy. This will be discussed in Chapter 11 *Development of a dedicated conservation strategy*. Before, the application of the different states of conservation will be illustrated, using the case studies already mentioned in

Chapter 8 *Mutual relationship between the heritage values, historic concrete and state of conservation.*

10.3 Fort Bezuiden Spaarndam (1897-1901)

The relevance of the historic concrete of Fort Bezuiden Spaarndam (1897-1901) regarding the history of concrete technology was discussed in Section 8.5. Special aspects were the presence of different types of original concrete and local remains of green, supposedly camouflage paint. The ceasing of the military function can be seen in the fact that the paint has not been renewed. Degradation symptoms are present, mainly caused by the original material choice and design.

In the state before the intervention in 1996, the concrete showed signs of considerable damage (cracking, water infiltration, leaching and detachment). Not only the appearance but also the original material was endangered. The main underlying causes were ASR and lacking expansion joints. The causes of damage are the direct result of the former state-of-the-art of concrete technology, and contradict the original intention of making a high quality concrete.

From a technical analysis, it can be concluded that without intervention, the damage process might still continue. Assessment of the remaining ASR reactivity of concrete by means of expansion test would be recommended. If still active, protective measurements should be considered but it can be expected that the ASR will continue in a much slower pace than in the previous decades. Regarding the lacking expansion joints, cracks already appeared to compensate the stresses. Through these cracks, water infiltrations are possible, causing secondary damage. As the concrete is not reinforced, there is no risk of corrosion. For the usability of the building, the interior should remain dry.

A state below the acceptable state of conservation would be reached when the variety of historic concretes and the original structure cannot be perceived anymore. The question is whether to interpret or not the damage caused by ASR as an expression of the original, specially chosen constituents. If so, its presence can be considered as part of the ideal state and not necessarily a threat. The remaining original green paint should remain present, as it is evidence of the original function of the fort and of historical value in context with the construction history and appearance of military buildings.

As the original concrete is of high value, the ideal state should allow its unchanged presence on-site. The damage symptoms caused by ASR and lacking expansion joints can be accepted as part of the ideal state; they are closely related to the building technological values of the fort and reflect the progress of concrete technology, including trials and errors. The original appearance does not have to be reconstructed as the ceasing of the military function caused the paint to disappear gradually; the remains of camouflage paint should be kept and protected to document its history and design of early military buildings. The conservation aim would include the following aspects:



(a)



(b)

Figure 10.2 Façade of the emplacement after being painted entirely white (Hofplein railway viaduct, situation 2012, compare also with Figure 8.16a). a) Overview. b) After painting, the different materials (Blue Belgian limestone, artificial sandstone render) cannot be distinguished anymore from a distance. Damages have not been treated, material loss is expected to increase, and the corroding reinforcement might gradually stain the white paint.

- Preserving the original material on-site.
- Retarding further deterioration to preserve as much historic concrete as possible.
- Preventing secondary damage which could cause further material loss.
- Documenting the original paint as its current state is fragile.
- Improving the usability of the fort (e.g. water infiltrations).

The main criterion for a conservation strategy is minimal loss of original material, both historic concrete and paint, during time and preserving original details of former concrete technology (workmanship, detailing, and mix design).

10.4 Hofplein railway viaduct (1900-1908)

The design and construction of the Hofplein railway viaduct (1900-1908) played an important role in the development of reinforced concrete technology in the Netherlands (see Section 8.6). In addition, the viaduct represents the discussions related to aesthetical treatment of concrete at the beginning of the 20th century. The original concrete, surface and reinforcement are in most cases still present. In the 1950s, large-scale interventions were carried out to improve the functionality as a railway viaduct.

In the actual state of conservation, leaking joints of the 1950 extension on top of the viaduct are causing seepages, biological growth, soiling and corrosion. Cracking in the abutments is common; the depth and cause of the cracks have not been investigated yet.¹ Due to several past interventions, the original surface finish is only locally visible. Colour variations of the render caused by the fire during the Second World War in May 1940 can be recognised under locally missing paint. In some parts the original surface finish is lost and replaced with smooth repairs. It is expected that corrosion will continue and locally increase due to leakages, causing a loss of both reinforcement and surface. In other parts, more fragments of the original surface finish will become visible during time with the detachment of the paint.

During repairs in 2011, the façade of the emplacement was painted homogeneously white (Figure 10.2). The intervention was carried out to improve the appearance of the façade of the newly opened shopping centre. The painting is intended to be temporary although the reversibility of the intervention has not been discussed. Therefore, present damage and damage symptoms were not treated. In the meantime, research on suitable repairs options for the façade is being considered. This intervention allows a real size mock-up of the effects of painting the

¹A technical survey of the structure has not been carried out yet in practice. With the intended transformation of the Hofplein railway viaduct in the near future, technical investigations of the viaduct including causes of damage are currently considered.

entire façade white: all evidence of the original material and colour of historic concrete buildings is lost and a false impression created.

In an ideal state of conservation, the viaduct would be able to tell about the structural and aesthetical design of concrete structures at the beginning of the 20th century. This includes the textural and colour details of the façade and the preservation of the variety of reinforcement types and specially chosen concrete mix design. Locally exposed reinforcement gives insight into the innovative design of reinforced concrete structures but should be protected from further material loss. The reinforcement embedded in the concrete should remain intact.

In the actual state of conservation, the state of the historic material related to the heritage values has come below the acceptable state. The original appearance is impeded as both concrete and natural stone plinth have been painted, but also due to mismatching repairs and to local soiling and spalling (Figures 8.16 to 8.21). The reinforcement is endangered as corrosion is locally already in the propagation phase and should be stopped to prevent further loss of reinforcement and surface. An intervention is therefore required, and the original surface appearance should be restored. As the railway function has ceased, functional thresholds are more flexible as they can be adapted to the requirements resulting from preservation of the heritage values and technical performance.

The conservation aim for the Hofplein railway viaduct should include the following main criteria:

- Restore/reconstruct the colour, texture and pattern of the surface using as much as possible the still existing render.
- Preserve and expose the discolorations caused by the fire in 1940.
- Preserve the different types of reinforcement, including their varying geometry and connection methods.
- Preserve the original concrete.

The 1950s interventions (columns, extensions of paths) can be accepted as they reflect the development of railway infrastructure and neither affect the surface nor the reinforcement. A prerequisite is that they do not cause further harm (e.g. leaking joints) towards the historic concrete dating from the original construction phase.

10.5 Earth retaining walls of the unfinished Groot Museum (1921)

The earth retaining walls of the unfinished Groot Museum (1921) designed by H. van de Velde for the art collectors Kröller - Müller in the national park Hoge Veluwe, are the only remaining artefacts of the design on-site, indicating the once intended grandeur of the museum (see Section 8.7). Several traces exist which

testify to the ceasing of works in 1922, such as remains of formwork, the unfinished state of the walls and the blocks of natural stone spread throughout the landscape. The walls have been left as ruins for decades and slowly merged with the landscape of the natural park.

In the actual state of conservation, the historic concrete shows damage. The concrete has spalled and the reinforcement is locally exposed. The surface texture varies; in protected areas, the original imprint of the timber formwork is visible, in other more exposed parts the textural details have eroded. Biological growth is common (Figure 8.29). No interventions or repairs are present as the walls were considered as a ruin and therefore not maintained. Only the walls of the intended sculpture yard (Figure 8.23) are in fact earth retaining, the initially intended earth retaining walls of the terrace are free-standing as the terrace was never built (Figure 8.24).

In this case, the actual state of conservation can be considered as close to the ideal state. The architectural historical values, general historical values and building archaeological values can be clearly experienced such as the once intended grandeur of the project, the ceasing of the works and the merging with the landscape. The present damage symptoms pose now no threat to the heritage values. The deterioration underlines the ceasing of the works and the transformation of the building site into a ruin. The acceptable state is mainly determined by the condition of the historic concrete and ascribed heritage values. As the walls are without function, functional thresholds relate mainly to safety, such as preventing the collapse of the walls and injuries caused by spalling concrete pieces. Compared to earth retaining walls with a function and proximity to people, here reduced safety factors can be considered.

The question is whether in the expected state of conservation, the situation is similarly positive or if the acceptable state of conservation will be reached. Further deterioration cannot be excluded considering the intended perpetual heritage service life (Section 9.3.4). Corrosion and erosion will continue causing a local loss of concrete and reinforcement. The relative amount of material loss is expected to be less than in the past as the most vulnerable parts have already spalled. Biological growth will continue as well, which is appreciated as it reflects the merging of the walls with the park.

An intervention is currently not necessary, but a preventive intervention to decelerate material loss could be considered. The criteria thereby would mainly relate to the surface of the walls, as here most traces of the construction history can be found and of the history of the building:

- The expected state of conservation after intervention should be explicitly above the expected state of conservation without intervention as currently the walls are close to the ideal state.
- The ruin-like atmosphere should not be disturbed.
- The textural details and remaining formwork fragments, and the biological

growth should not be lost.

- The starter bars should remain exposed.
- The outlines and dimensions of the (earth retaining) walls should remain perceivable.

10.6 Conclusion

In practice, decisions whether intervention is necessary and the decision on the type of intervention are mainly based on the treatment of damage symptoms. The preservation of heritage values is not integrated in technical discussions. Obstacles are often the uniqueness of each conservation project and the difficulties to combine technical and conceptual demands when trying to find an appropriate intervention.

A solution is first to discuss the conservation aim and individual criteria for a conservation project without considering limitations and contra-indications. By this, the focus of the discussion is laid on the monument specific requirements; the involved specialists are acquainted not only with the monument but also with the demands and limitations of the involved disciplines.

In order to develop a conservation aim, which considers both technical demands and the preservation of heritage values, an approach was proposed in this chapter. This approach is based on the relationship between four different states of the historic concrete: the actual state of conservation, the expected state of conservation, the ideal state of conservation and the acceptable state of conservation. An analysis of the relation of the different states indicates the need of intervention and criteria of the conservation aim. The added value hereby is that not only technical and functional requirements are considered, but also requirements based on the preservation of heritage values.

An essential prerequisite is to have objective information of the actual state of conservation for all aspects - technical performance, functionality and heritage values - which is only possible if sufficient pre-investigations are carried out. In order to have an objective reference point to evaluate the efficiency of an intervention, a prognosis of the expected state of conservation is necessary.

By this, an orientation can be given to all parties of what would be the best solution, and criteria deduced of the characteristics of a conservation strategy. Besides agreeing on what would be the best state, an acceptable state should be discussed to identify the boundary conditions for an intervention. This is essential, as in most cases not all aspects of the ideal state can be achieved.

In the three discussed cases - Fort Bezuiden Spaarndam, Hofplein railway viaduct and the earth retaining walls of the unfinished Groot Museum - identifying the four different states and the formulation of the conservation aim helped to clearly formulate whether intervention is necessary and to assess what the main aim of the intervention should be or should have been. Compared to normal repair strategies, a shift of the emphasis can be noticed as not the treatment of damage

was the main objective, but a holistic conservation aim which considers technical performance, degradation, functionality and heritage values. The conservation aim indicates the minimum and ideal criteria of a historic structure for both technical and cultural historical aspects. It functions as a reference point for the following step, the development of a dedicated conservation strategy, which will be discussed further on in the next chapter.

Chapter 11

Development of a dedicated conservation strategy

Chapter Outline

In the concluding chapter of Part III of this thesis, the development of a dedicated conservation strategy will be discussed. The previously introduced four states of the historic concrete will be used again to develop case specific criteria related to the conservation aim, and to evaluate different possible conservation strategies. Of the previously introduced case studies, one case - Fort Bezuiden Spaarndam - will be continued and a possible dedicated conservation strategy shown, addressing the technical feasibility and demonstrating why a focus on technical aspects only is not sufficient.

11.1 Introduction

The development of a dedicated conservation strategy will, in most cases, not be straightforward. The criteria to evaluate whether a strategy fulfills the conservation aim regarding technical performance, functionality and preservation of heritage values are not necessarily harmonised. In most cases, no obvious solution exists which fulfills all criteria. Instead, it is necessary for each conservation project to develop and compare different strategies, and to identify the most appropriate under the case specific boundary conditions, and which respects the case specific conservation aim. One and the same conservation strategy cannot be applied for different monuments as each has a different conservation aim, influenced by varying heritage values and material properties. In addition, not all repair techniques can be applied equally well, as the properties of different historic concretes can vary strongly; the same applies to the underlying causes of damage.

In the previous chapter, the analysis of the four different states of the historic material indicated whether the historic concrete and the ascribed heritage values are either at risk or near the ideal state. The characteristics of a required intervention, if necessary, were identified. By then, the monument specific boundary conditions can be formulated such as technical demands (for example treating, retarding or accepting degradation), the urgency of the intervention, and the impact of interventions on material and heritage values.

The previously introduced four different states of the historic material can also be used to evaluate the effectiveness of a suggested strategy. Criteria should be besides the technical performance of the historic material and functional demands, the performance of the heritage values. The formulated criteria allow a judgement on whether a suggested strategy would create an expected state of conservation, which would be closer to the ideal state than without intervention. The aim is to develop a realistic strategy that allows obtaining the conservation aim as closely as possible. In this chapter, criteria to evaluate and compare different conservation strategies will be introduced and illustrated with the previously discussed case Fort Bezuiden Spaarndam.

11.2 Criteria for a dedicated conservation strategy

General, conceptual demands towards interventions such as retreatability and reversibility, compatibility, and the demands of a perpetual heritage service life should be discussed for every conservation campaign (see Chapter 9 *Impact of repairs on historic concrete and heritage values*). In addition, case specific boundary conditions must be discussed in order to determine the characteristics of a dedicated conservation strategy. These can be formulated based on the monument specific conservation aim, the properties of the historic concrete, the degree and type of degradation, and the type of heritage values to be preserved.

Based on the conservation aim, and independently from a specific repair technique, a review should be made of which material characteristics should be preserved, which degradation mechanism and symptoms prevented or treated, and whether or not material losses are acceptable. Similar criteria can be made with respect to the impact of a repair technique, which was previously discussed in Chapter 9. It has to be understood, that in most cases minor or major side-effects of an intervention on either the material or on the heritage values may occur.

The acceptable impact of an intervention on the historic material and on the heritage values has to be mutually agreed upon. Using the previously introduced acceptable state of conservation and the ideal state as orientation, case specific criteria can be formulated. In Table 11.1, an overview is given of different aspects which should be discussed when deciding on the criteria for a suitable conservation strategy. This includes:

Table 11.1 Overview of possible aspects, which should be discussed when formulating the criteria for a dedicated conservation strategy.

Degradation	Appearance
Damage aspect:	Parameters of appearance:
Symptoms	Colour
Causes	Texture
Secondary damage	Geometry
Conservation aim:	Conservation aim:
Treat degradation	Actual appearance
Retard degradation	Reconstructed appearance
Accept degradation	Modified appearance
Material loss	Intervention
Component:	Conceptual demands:
Surface	Retreatability
Bulk	Compatibility
Reinforcement	Durability
	Heritage Service Life
Conservation aim:	Characteristics:
Material loss is acceptable	Preventive intervention
Material loss is limited	Curative intervention
Material loss is excluded	Emergency intervention
Restraints	
Material properties of historic concrete	
Time	

- The type of degradation and whether it should be treated, retarded, or even accepted.
- The impact of the intervention on the appearance of the historic concrete and which appearance is envisioned.
- The degree of acceptance of material loss and if differentiations can be made between the surface, the bulk and the reinforcement.

Other aspects are whether the intervention should be curative or preventive, or if the intervention has to be carried out quickly due to acute endangerment of safety or heritage values. The properties of the historic concrete determine the boundary conditions as well as they can complicate or even restrict the application of some repair techniques. One common example is the lacking connection of historic reinforcement influencing the feasibility and costs of electrochemical repair methods. The geometric properties of concrete elements can limit the type of intervention as well if the concrete cover cannot be increased. External aspects such as the costs or availability of a repair technique, or safety and functional requirements should be considered in practice as well. These however are outside

the scope of this thesis. From the resulting description different repair approaches can be reviewed for their suitability.

11.3 Evaluation of different conservation strategies

A proposed conservation strategy should be reviewed for its feasibility, not only in technical terms but also with respect to the impact on the historic material and heritage values. In most cases, no ideal approach exists and a mutual consent has to be made. In order to make a justifiable decision, it has to be understood why a chosen strategy would be better on the long-term than others, and that the key issues of the conservation aim have been fulfilled. The question is how to evaluate different strategies.

A prerequisite is to understand the risks and benefits of a proposed strategy and to predict a new state of conservation after the intervention. It should not be forgotten, that also here the evaluation of the new expected state of conservation should be based on all three, the technical performance, preservation of the heritage values and the functionality of the monument. Applying the case specific criteria, it can be evaluated for which aspects an improvement would be achieved, and whether for some aspects no improvement or even a decline would occur.

More complicated is the evaluation of different scenarios during several intervention cycles, which is however necessary considering the required perpetual heritage service life. In Figure 11.1, a (theoretical) comparison of two different strategies is made: without intervention the historic material and related heritage values would go below the acceptable state; therefore an intervention is considered. Strategy A would improve the situation, Strategy B would immediately create a state that is lower than the actual state of conservation. In such a case, it would be evident to choose Strategy A.

The question is whether during a second intervention cycle a similar success might be achievable or, if by choosing strategy A in the first intervention cycle other (possibly more suitable) options have been excluded for future intervention cycles. In this way, several strategies can be compared, using the actual state of conservation and the expected state of conservation as benchmarks and the conservation aim as orientation.

When illustrating such strategies with examples of common practice, it becomes obvious that Strategy A is not always chosen. Commonly, the three aspects (preservation of heritage values, technical performance and functionality) are not considered together. More commonly neglected are the consequences of successive intervention cycles. For example, for the two cases studied during the initial phase of this research, similar problems were identified (Section 1.3.2 *Review of Dutch concrete conservation practice*). For Parksluizen Pumping Station, the main aim was to preserve the appearance, and the technical performance considered secondary. A less invasive intervention was chosen but the underlying degradation problems not addressed. In order to compensate for the less durable strategy, suc-

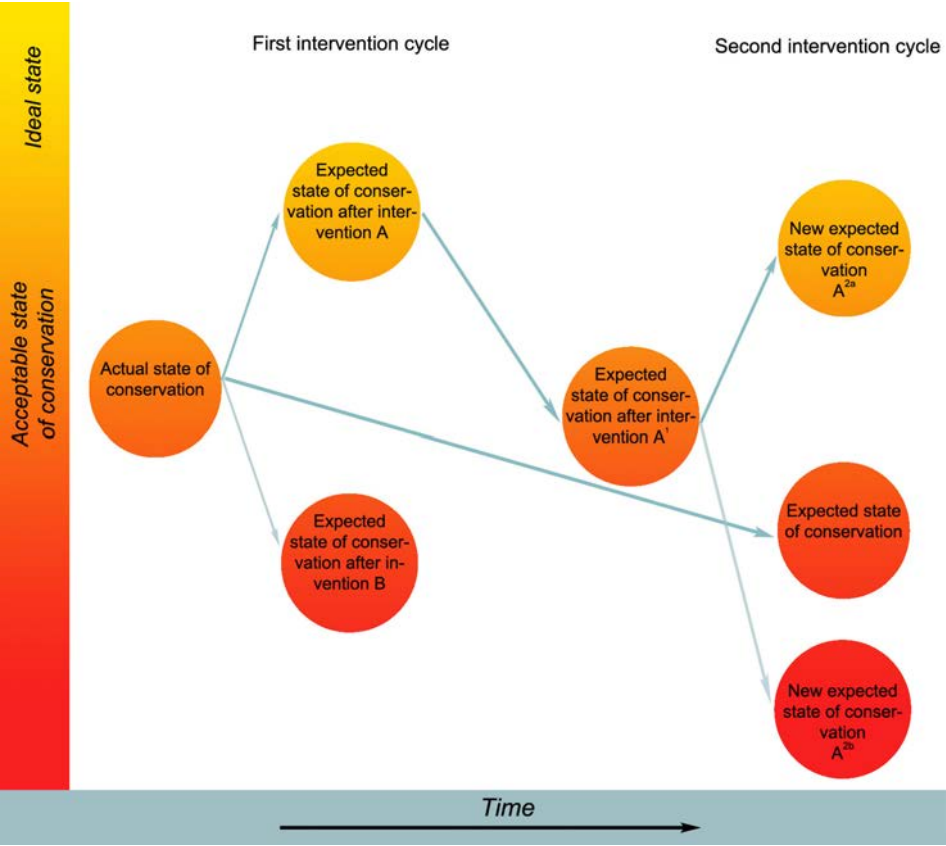


Figure 11.1 Example where the state of conservation is close to the acceptable state, initiating intervention: Strategy A would result in a state of conservation closer to the ideal state, Strategy B would immediately create a less acceptable state. However, in order to meet the requirements of a perpetual heritage service life, successive cycles have to be considered. In this case, the overall success of strategy A depends on whether after the first cycle strategy A^{2a} or A^{2b} can be followed.

cessive intervention cycle should have been considered, and their characteristics and frequencies identified. In case of Fort Spaarndam Bezuiden, the conservation carried out in 1996 focussed on mainly technical aspects, and the intervention caused a loss of heritage values. Therefore, the state of conservation after intervention was below the actual state of conservation when using criteria based on the technical performance, preservation of heritage values and functionality.

In Section 11.4, the possibilities to develop and evaluate a conservation strategy will be illustrated by the previously introduced case - Fort Bezuiden Spaarndam. Of the three cases discussed in Chapter 10, the historic concrete of Fort Bezuiden Spaarndam is of highest historic value. In addition, the fort represents dilemmas

where several damage symptoms are present, and cause of damage and heritage values (partially) have the same material origin. The other two cases, Hofplein railway viaduct and the retaining walls of the unfinished Groot Museum, will not be further discussed in detail. However, based on the conservation aim developed in Chapter 10, a quick outline of the characteristics of a possible dedicated conservation strategy will be given.

For the retaining walls of the unfinished Groot Museum it was already considered that the actual state of conservation is near the ideal state, and that the expected state of conservation will not pass below the acceptable state of conservation soon. An immediate intervention is not necessary. As degradation is present and will continue in the future, a preventive intervention can be considered. Any dedicated conservation strategy should decrease the loss of historic material and not destroy historical traces on the surface. However, common repair techniques cannot fulfil the main criteria of the conservation aim, namely to preserve both the historical traces and the original material (concrete surface and bulk, formwork remains, visible reinforcement, biological growth), whilst maintaining the ruin-like atmosphere (Heinemann, 2008a). Technically, repair would be possible, but common techniques, such application of repair mortars or electrochemical repair methods, would result immediately in an unacceptable state of conservation, as the ruin-like atmosphere would be destroyed. No intervention can be acceptable in this case as it offers the nearest state to the ideal state.

The Hofplein railway viaduct exemplifies situations, which are related to the restoration and reconstruction of surface finishes. In an ideal state its appearance would demonstrate the original material (Blue Belgian limestone plinth, artificial sandstone render) and colour combination (dark grey-blue and beige, reddish), including their respective surface textures. The still present original reinforcement testifies for the underlying pioneering work regarding structural design and choice of reinforcement systems. The actual state has gone below the acceptable state of conservation. The original appearance is not visible anymore; however, the original surface is locally still present but covered. The original reinforcement is endangered by corrosion; without intervention, the pace of degradation will accelerate. The conservation aim would be to restore the appearance and preserve the original reinforcement. Preventive measures concerning the preservation of the reinforcement should be considered, also to prevent future cracking and spalling of the original concrete and render. A dedicated conservation strategy that partially converges with the conservation aim would in principle be possible. The main aspects would be to restore the original appearance and to preserve the original reinforcement. The main challenge is to develop a suitable approach, especially regarding the cleaning of the façade, mortar composition and tooling of the surface.

11.4 Fort Bezuiden Spaarndam (1897-1901)

As concluded in Section 10.3, the ideal state for Fort Bezuiden Spaarndam (1897-1901) would include the unaltered presence of the original material - both historic concrete and paint - because of its high cultural and historical value. Present damage symptoms (cracks, deposits on surface) caused by alkali-silica-reaction (ASR) and lacking expansion joints are acceptable. In the actual and expected state of conservation, the original material is endangered, mainly by secondary damage caused by water infiltration. In addition, water infiltrations can limit the usability of the fort. A conservation strategy that minimises material loss and preserves original details of former concrete technology (workmanship, detailing, and mix design) is envisioned.

The impact of conservation techniques on the surface must be considered, as the remains of the original paint should not be endangered by the intervention. When evaluating the feasibility of a conservation strategy, the specific properties of the historic concrete of Fort Bezuiden Spaarndam should be kept in mind. The concrete is not reinforced; therefore, there is no risk of corrosion. However, stresses caused by thermal movement of the walls cannot be partially compensated by a reinforcement, aggravating the movement of the cracks. Other properties, which have to be considered are local voids such as honeycombs and higher porosity caused by manual compaction and chosen coarse aggregate, and the presence of moisture in the walls. An advantage is that repair works carried out on similar forts of the Stelling van Amsterdam can be used as reference to indicate the feasibility of possible interventions.

In this section, different strategies to achieve the conservation aim of preserving the historic concrete are compared together with their influence on the remaining paint. A “do-nothing” strategy is not considered as the description of the expected state in Section 10.3 showed that this would result in an unacceptable state.

11.4.1 Preservation of the original concrete and paint

The historic concrete is endangered by ASR and lacking expansion joints, both causing cracking and leaching. The main threat is further material loss due to water infiltrations. To achieve the ideal state, or at least decelerate degradation and improve the expected state, the causes of damage and symptoms should be addressed.

A dilemma is that ASR cannot be cured yet, degradation can only be delayed or symptoms treated, the structure replaced or strengthened (Section 9.4 *Repair techniques*). Demolishing and replacing the historic concrete is excluded in this case, as it would immediately cause an irrevocable loss of historic material, i.e. accelerating the loss of heritage values which otherwise might have only occurred in the remote future. Therefore, the pace of ASR - if expansion test would confirm that it is still active - and the impact of the symptoms should be mitigated.

The three main components involved in ASR are cement, containing alkalis, siliceous aggregates and moisture. Most alkali and reactive silica originally present in concrete would have been consumed during the reaction until now. If further research indicates that the reaction might still continue, one should attempt to reduce the ingress of moisture. As the curing of ASR in existing structures is researched (see Section 9.5), the use of experimental techniques should be balanced and only considered when *“the efficacy [...] has been shown by scientific data and proved by experience”* (Venice Charter, art. 10, ICOMOS, 1964).

Preventing moisture ingress can mitigate both ASR (if still active) and prevent or reduce secondary damage. Currently, moisture can penetrate through cracks in the exterior walls and roof. It is technically possible to make the roof watertight (e.g. with membranes) and has been done successfully in the 1996 conservation campaign. This intervention is reversible and retreatable.

The presence of cracks in the wall is not an immediate but a potential future threat, as leaving the cracks untreated may increase the risk of freeze-thaw damage. To prevent premature failure of crack repairs, it is necessary to know whether the cracks are still active. Active cracks require a different approach, and the elastic properties of the repair material have to be chosen in accordance with the expected movement of the cracks. Such active cracks appeared at Fort Bezuiden Spaarndam as no expansion joints were present (see Figures 11.2 to 11.3). Moisture ingress through these cracks is common, and in combination with voids, moisture can easily penetrate into the depth of the concrete (Figures 11.3 to 11.5). The presence of voids in the concrete is more likely due to the use of crushed rock as aggregate and the manual compaction applied. For the choice of a repair material that could fill the cracks and compensate the thermal stresses, parameters are currently missing to define its properties. As this damage symptom is common for the plain concrete forts of the Stelling van Amsterdam, different previous interventions can be studied/evaluated for their impact and effectiveness (Figures 11.2 and 11.3).

Injection of the cracks is problematic due to voids, and the presence of moisture in the concrete. Injections have been tried out during the conservation campaign in 1996 and new expansion joints using elastic sealants to compensate the stresses had been created (Figure 11.2a). The execution of the repair was difficult, voids and interstices complicated the injection. The new expansion joints were empirically dimensioned, not taking into consideration the depth of the walls (ca. 1.50 m) and the movement of plain concrete walls. The intervention failed due to problems with injecting the concrete and the lack of reference data of the thermal movement of such plain concrete structures.

During preparation, limited material loss is unavoidable, as the cracks would have to be cleaned and the geometry adapted to achieve a more durable repair. The filled cracks would remain visible as an elastic sealant and not a cementitious repair mortar would be used. A different option would be to seal the active cracks with a rubber strip, which would however have a stronger impact on the appearance.

Concluding, a treatment of active cracks cannot be carried out without detailed investigation of the movement of the concrete when exposed to thermal stresses,

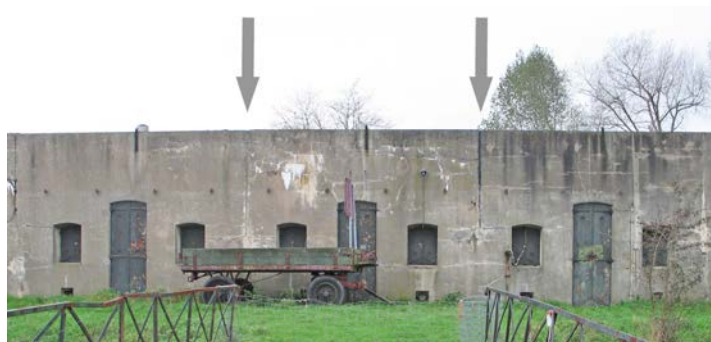


Figure 11.2 Example of untreated cracks at the former construction joints caused by thermal stresses (arrow) (Fort Benoorden Spaarndam, 1897-1901, situation 2006).



Figure 11.3 Two different interventions of the active cracks caused by thermal movement. a) Example of a failed repair of an active crack: the concrete was injected and new expansion joint created and filled with an elastic sealant; yet, the cracks reappeared (Fort Bezuiden Spaarndam, 1897-1901, situation 2006). b) Example of an untreated crack showing the risk of moisture ingress (dark zone is moisture, visible after a rain shower); the parapet has not been covered, allowing additional moisture ingress from the top (Fort near Vijfhuizen, 1899, situation 2008).



Figure 11.4 Example of honeycombs; plain concrete wall with crushed rock, cut through during a previous intervention (Fort near Hoofddorp, 1904, situation 2006).



Figure 11.5 Example of seepage through former construction joints and cracks caused by thermal stresses in the interior of the fort (Fort Bezuiden Spaarndam, 1897-1901, situation 2006).

as the properties of the plain concrete differ from those of ordinary reinforced concrete. The movement is affected by lacking reinforcement and inhomogeneity in the concrete. In current state-of-art, any crack repair would be experimental and should only be applied when sufficient scientific data are available on the success of intervention (Venice Charter, art. 10, ICOMOS, 1964).

In case the cracks are inactive, investigations can be made for a compatible repair mortar to fill or inject the cracks (Sections 9.4.1 and 9.4.3). As no reinforcement is present, considerations of future compatibility with electrochemical repair methods are not necessary. Although the appearance of Fort Bezuiden Spaarndam is not the main criterion of the conservation aim, the aesthetical impact of the repaired cracks should be considered (Figure 11.6). To underline the monolithic appearance of the fort, repairs should not be visible from distance. It is technically possible to adapt the colour of a repair mortar to the surrounding concrete, yet it should be considered that the colour can deviate overtime due to moisture and ageing. As the historic concrete is covered with a thin layer of render and no aggregates are visible, covering repaired areas with a similar render or using a repair mortar with a similar appearance could be considered.

For all crack repairs, it should be taken into account that the removal of the repair material after failure will be accompanied with loss of historic concrete. Before applying a new repair mortar, the cracks have to be cleaned and historic material will be removed. The failure of the repair will cause material loss as well, the degree depending on the failure mechanisms of repair mortars, where debonding often takes place in the parent concrete. Therefore, for the choice



(a)



(b)

Figure 11.6 Example of the visual impact of repaired cracks (Fort Bezuiden Spaarndam, 1897-1901, repair 1996). a) Situation before intervention (1995) with visible cracks and deposits from leaching (picture R. P. J. van Hees). b) Situation after intervention (2006); the repair mortar was not adapted in colour, emphasising the pattern caused by the cracks (NB Painting of the façade was intended but not performed, therefore the repair mortars were not adapted in colour).

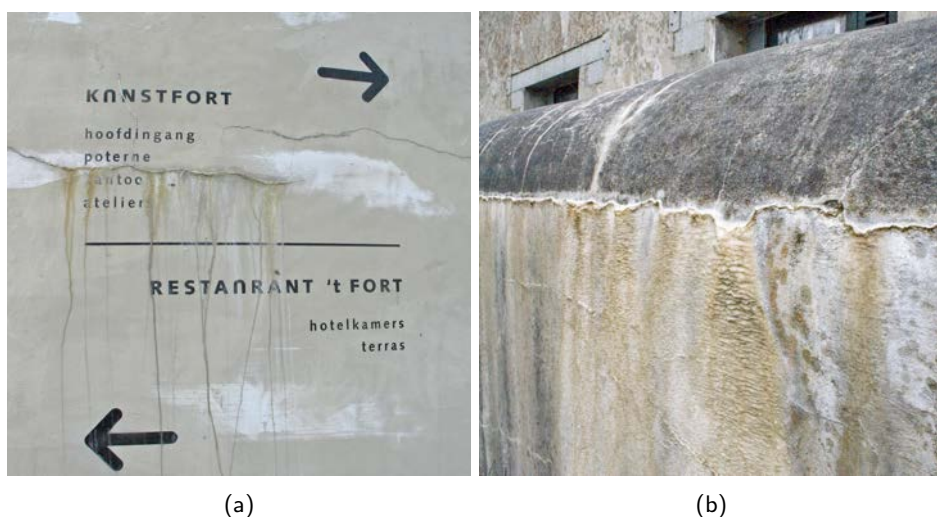


Figure 11.7 Two examples of the reappearance of leaching after intervention. a) Reconstructed paint showing reappearance of damages: leaching and subsequent deposition and cracks (Fort near Vijfhuizen, 1899, conservation 2003-2005, situation 2006). b) Reappearance of leaching ca. 10 years after façade cleaning; the concrete was not protected from moisture ingress (Fort Bezuiden Spaarndam, 1897-1901, intervention ca. 1996, situation 2006).

of a suitable repair material, its durability has to be considered. It has to be controlled that it fails either in the interface between the historic concrete and the repair material or in the repair material itself. Attention is required when choosing the repair mortar as common concrete repair mortars are designed that the failure occurs in the parent concrete.

The application of surface treatments to limit water ingress through the façades will not be further discussed, as several indications exist questioning their effectiveness. Contraindications are the amount of cracks present, the presence of active cracks, and the moisture content in the walls. Due to their thickness (ca. 1.50 m) they would remain humid for a long time and not all moisture sources can be eliminated (earth retaining walls). For other forts with similar problems attempts were made to treat the symptoms of ASR and to mitigate degradation by injecting the concrete and applying a coating (Bakker, 1996), however, on the long-term they were ineffective (Figure 9.24). More concerning is, however, the immediate impact on the remaining original paint. The major threat is hereby cleaning before application, for both the first and successive treatments.

Arguments might be put forward that the preservation of the historic material outweighs the preservation of the historic paint, allowing a surface treatment. The remaining paint can be used as guidance to create an appearance similar to the original appearance. Other benefits of applying a surface treatment would be to

disguise repaired areas. It has to be kept in mind that surface treatments would require regular maintenance and should be integrated in maintenance plans. A pristine appearance of the fort would be unlikely as leaching of the concrete could still be possible (Figure 11.7). Presently, leached deposits on the surface mainly affect the visibility of the paint, and less the historic concrete. The deposits can be removed but attention has to be paid whether a removal would cause damage to the surrounding concrete and loss of original paint. It has to be kept in mind that leaching will occur again as long as sufficient moisture is present in the concrete, questioning the usefulness of the cleaning (Figure 11.7).

11.4.2 Conclusions Fort Bezuiden Spaarndam

Due to the value of the historic concrete, its preservation is essential to achieve the ideal state; a second aspect of the ideal state would be that remains of the original paint would be preserved. The analysis of the four states of the historic concrete in Section 10.3 resulted in intervention being necessary as in the actual state of conservation the historic concrete and related heritage values are threatened. The underlying causes of damage are related to former construction technology. Therefore, the damage symptoms can be accepted as an expression of former concrete technology. Looking at the expected state of conservation, further material deterioration is likely to occur, especially due to secondary damage.

In this section, it was investigated what the characteristics of a dedicated conservation strategy would be, including its feasibility. Reviewing possible repair techniques showed that avoiding any further material loss is not possible. The underlying dilemma is that cause of damage and heritage values are too closely related in terms of material origin and that too little experience exists with the intervention of such plain concrete structures. However, eliminating the main sources of water ingress can decrease the risk of further material loss.

A realistic and dedicated conservation strategy for Fort Bezuiden Spaarndam would be to eliminate the main sources of moisture ingress through the roof and the major cracks. As most cracks are active, their repair is difficult, and further research on their behaviour is necessary. Similar obstacles exist when deciding to change the existing cracks into expansion joints. Therefore, any attempt to treat the cracks requires fundamental research and local try-outs before application. Surface treatments are not advised as they are expected to negatively affect the remaining paint. In addition, the presence of moisture in the concrete and of active cracks questions the durability of most surface treatments.

Due to the movement of the cracks and the moisture present in the structure, the durability of a repair might be quite limited and options should be considered which allow a future replacement of the repair without losing too much of the original concrete. A balance has to be found between the capability of a repair mortar to compensate movement on the one hand and a weaker interface between original concrete and repair on the other hand. In this way, for each failure and repair cycle less material would be lost. The width of the crack has to be considered

in order to decide whether an intervention is necessary. The main criterion is here the exposure of the cracks towards rain and the width, influencing the quantity of water penetration. As no reinforcement is present, the risk of corrosion does not have to be considered and smaller cracks can remain untreated.

The ideal appearance of the concrete includes the visibility of the remaining paint and the acceptance of damage symptoms. As interventions are expected, their influence on the ideal appearance must be taken into account. Caution is advised during preparation activities such as façade cleaning in order not to destroy the paint. The applied conservation techniques should neither cover the paint nor disturb the appearance of the fort.

The presence and reappearance of damage symptoms, such as leaching and cracking, has to be accepted. Additionally, it has to be accepted that regular monitoring of the performance of the repairs and of the occurrence of secondary damage has to be carried out. Regular maintenance cycles and repair cycles (replacement/repair of cracks) are necessary and have to be integrated in the conservation strategy. Continuous use of the fort would enhance the possibilities of regular inspection and maintenance.

The proposed dedicated conservation strategy does not eliminate all future degradation and further material loss has to be accepted. However, the relevant aspect is that compared to no intervention at all, i.e. the expected state of conservation, the new expected state of conservation after conservation will be improved. Such an approach, which tolerates limited further deterioration, can be legitimated as long as the historic concrete is preserved in a sufficiently sound state to transmit its heritage values, and as long as the safety and usability of the building are not endangered. Compared to a normal repair approach, the main difference lies in the criterion to preserve as much as possible of the original material during several intervention cycles and the acceptance of damage symptoms.

Risks are the lack of experience with the conservation of early plain concrete structures. Therefore, the experimental character of the conservation has to be kept in mind and necessary underlying research must be carried out. As many similar historic concrete objects exist at the Stelling van Amsterdam and considering their relevance as a UNESCO World Heritage site, a joint research on this topic is advised. Similarities and differences in degradation mechanism (e.g. secondary ettringite formation is known from some forts), damage progress and intervention options should be investigated, both technically and in regard to possible influences on heritage values. A long-term observation and comparison of the effectiveness of interventions is essential to improve the prediction of future interventions.

11.5 Conclusions

In this chapter, an approach was suggested to develop a dedicated conservation strategy, building up on the insight made in the previous chapters. The crucial point is to understand the mutual relationships between material properties, heritage values, state of conservation, and impact of repair materials including several intervention cycles. Similar conclusions have been drawn and previously discussed in Chapters 8 to 10.

The suggested approach was applied for the case Fort Bezuiden Spaarndam (1897-1901). For this case, a “perfect” conservation technique allowing treatment of the main causes of damage while preserving the heritage values does not exist; the major dilemma is that both cause of damage and heritage values relate to the original concrete. The application of the four different states however did indicate that an improvement of the expected state of conservation is possible. Equally important is that it showed that some commonly applied techniques would not have resulted in an improvement; on the contrary, they would have even aggravated the expected state of conservation, as some heritage values would have been irrevocably lost at a quicker pace than without intervention.

The case also showed that the development of a dedicated conservation strategy depends equally on the fulfilling of technical demands and on the preservation of heritage values. A too strong emphasis on one aspect causes often impairment of the neglected aspect: either heritage values are lost and therefore the right of the monument to be listed; or by risking deterioration, the monument itself or valuable historic material is lost, bringing both material and heritage values to risk. In practice, such unbalanced decisions are, however, too often made only focusing on one aspect, especially when no straightforward solution seems possible.

Chapter 12

Conclusions and recommendations

Chapter outline

In Part III, an approach was introduced to develop a dedicated conservation strategy, combining the knowledge developed in the first two parts of the thesis. In this final chapter, the results of this research are discussed, including a rehearsal of the identified problems and reflection on the initial research questions. Suggestions are made for further research and recommendations are given for concrete conservation practice.

12.1 Scientific results

In this final chapter, the results of this thesis are reviewed. In Section 12.1.1, the starting point of this research and the identified problems within the field of concrete conservation in the Netherlands are rehearsed. In Section 12.1.2, the original research questions are reflected and answers given based on the outcome of this research. The results and their meaning for concrete conservation are further elaborated in Section 12.1.3. To finalise, suggestions for further research, recommendations for practice (Section 12.2) and final conclusions are given (Section 12.3).

12.1.1 Identification of problems

Conservation of historic concrete is a recent field, and a critical review of current practice had not taken place yet. Conservation specialists still have to get acquainted with the history and properties of historic concrete, and still depend strongly on the expertise of concrete repair specialists for technical aspects. Until now, knowledge comes mainly from practice, where immediate results are required

and neither time nor financial resources are available to question an approach or address fundamental issues.

In the cases evaluated during this research, it was noticed that dilemmas and lack of guidance were not uncommon when decisions had to be made concerning the need and type of intervention. Questionable rules-of-thumb which conservation specialists gained when working with other, more traditional materials seemed not valid anymore, such as removing as little material as possible during repair or to repair like-with-like, as such repairs appeared not to be durable. On the other hand, overconfidence exists as well, and the complexity of concrete degradation and choice of compatible repair materials are not recognised. In addition, the specific material properties of historic concrete are often neither investigated nor understood.

Therefore, it is not surprising that - from a technical point of view - conservation of historic concrete has not always led to the best intervention possible, resulting in premature failure of repairs or to the application of mismatching patch repairs. Looking at previous interventions from a conservation point of view, it is not only the (occasionally poor) technical performance which stands out, but also that heritage values are clearly not integrated in the conservation process. If heritage values are considered, their assumably unavoidable loss is justified as their preservation was technically not possible, or their preservation is used as a defense for technically poor solutions. Often, in practice, decisions are either made to achieve a satisfying technical performance or to preserve heritage values, the latter generally on the level of making a repair look “pretty” and limiting material loss. A level allowing sophisticated discussions on the aims and possibilities of concrete conservation, has not been reached yet. Governmental and academic support is limited, also due to the fact that these institutes are not pro-actively investigating future challenges of conservation but their response is reactive to encountered problems.

Besides these general issues, three main underlying problems of conservation of historic concrete are identified. The first relates to the approach towards concrete conservation: Concrete *repair* strategies and techniques are uncritically applied to concrete *conservation* projects. Yet, the field of concrete repair has developed for entirely different goals than required for conservation. Repair mainly aims at preserving the function of a structure for a limited remaining service life whilst considering economic boundaries. The perpetual preservation of heritage values has never been a requirement for repair. The desire to increase the remaining service life of monuments, which usually outruns the service life of normal structures by decennia and in many cases (desirably) by centuries, is not taken into consideration when planning a repair strategy; the effects (and risks) of successive intervention cycles are neglected. The different criteria for conservation and related conceptual demands, which are often too abstract to implement, are not considered or even not known amongst the involved repair specialists.

A second problem concerns knowledge and education on construction and material history of the late 19th and early 20th century. In this period, the way of

constructing and the materials used underwent dramatic changes, with iron and concrete as the most prominent examples of new construction materials. Although buildings dating from this period are already considered to be part of our heritage, the material aspects of the construction history are neither systematically investigated, nor part of the education of future heritage care specialists. In practice, this means that heritage care specialists do not have the knowledge to carry out or evaluate technical and historical investigations of historic concrete buildings. These shortcomings influence the resulting value assessments, as the historic concrete is neither correctly identified nor evaluated in its historical context. As a consequence, decisions varying from the listing of buildings to the way of intervening and the evaluation of (performed) intervention are therefore made on an incorrect basis.

Detailed information is necessary to evaluate the state of conservation and to choose a suitable conservation technique. Many concrete conservation projects are based on assumptions instead of facts, as too little is known about the properties of the historic concrete and detailed surveys are not always carried out. For technical aspects, this means that the degree of deviation of the properties of historic concrete from modern concrete are not known, making not only the level of correctness of surveys but also the compatibility of commonly chosen repair techniques questionable. These limitations lead in practice to endangerment of a large part of our recent heritage, and to an increase of maintenance and repair costs as less compatible repair techniques may be applied. Detailed information is equally important to determine the relationship between heritage values and the historic concrete (for example, why is a certain concrete an outstanding example for a specific period); a prerequisite for the preservation of heritage values.

A third problem is the lack of cooperation between the involved disciplines, not only between experts but also in reference books and guidelines. Conservation is an interdisciplinary field, combining history, architecture, engineering, material science and conservation philosophy. The historic building and material are hereby the unifying object and the desire to preserve them together with the ascribed heritage values the unifying motivation. Each discipline has its own (sub) research questions, but the underlying main research question should be the same: how to preserve our heritage, which we as society consider significant, for as long as possible.

In practice, investigations are fragmented and neither coordinated in content nor in time, nor during decisions; potential synergies between experts are not realised. An interdisciplinary approach combining construction and material history with material investigation is usually not done. Heritage values are used on a categorical basis and are seldom explicitly related to the historic material. As a result, they remain too abstract and are not integrated in the conservation process.

A critical review of both conservation approaches and education of conservation specialists is necessary. Especially the separation of historical and technical aspects must be overcome in order to make conscious decisions about how we can and should interact with our built heritage. Examples for broader and deeper edu-

cation and approaches do already exist within the field of art conservation, and for buildings the discipline of historic *Bauforschung*.¹ However, experience with more recent periods and materials is scarce and a comparable training still does not exist in the Netherlands.

The encountered issues are not unique for historic concrete as for other historic materials similar problems are encountered during conservation. Yet what aggravates the situation for historic concrete is that less experience exists, which may contribute to wrong decisions.

12.1.2 Reflecting the research questions

The problems, both regarding knowledge and approach, encountered during the initial phase of this research led to the formulation of the research questions, which were introduced in Section 1.4 *Research objective*. In this section, the research questions will be reflected and answered.

How can historic concrete be preserved together with its ascribed heritage values?

Historic concrete can only be preserved together with its ascribed heritage values when the properties of the historic concrete, the heritage values, and their mutual relationship are understood. Consequently, the influence of degradation and repair on both material and heritage values have to be identified, and it has to be determined whether they pose a threat, are beneficial or indifferent. This requires detailed knowledge of historic concrete, the historical context and of the consequences of degradation and interventions for the historic material. In addition, heritage values and material properties have to be addressed together during the entire conservation process, starting from pre-investigation, damage assessment and formulation of the conservation aim to development, evaluation and choice of a conservation strategy.

How can a proposed conservation strategy be evaluated on its impact on both the heritage values and the technical performance?

As heritage values are qualitative, an evaluation of the impact of an intervention on them has to be qualitative as well, using case specific criteria. These criteria should be based on general conservation demands, on the heritage values to preserve, the state of conservation and the conservation aim, and agreed upon mutually and interdisciplinary.

¹ Although a German term, *Bauforschung* is commonly used in English, literally meaning building research. *Bauforschung* tries to integrate historical and technical aspects and is carried out by professionals, who are trained in building and architectural history, material science, building surveys, conservation philosophy and conservation techniques.

It has to be kept in mind that no universal strategy can exist for (concrete) conservation, as the combination of heritage values, material properties, degradation and conservation aim is unique for each conservation project. However, especially for prefabricated, mass produced historic concrete elements, a more systematic approach for technical questions could be developed; nevertheless, case specific criteria based on the specific heritage values and conservation aim might still require a modification of possible technical solutions. Therefore, the detailed understanding of which material aspects are essential for the heritage values is required, including which alterations of the historic concrete would affect the heritage values. The benefits and risks of different repair techniques have to be understood and reviewed according to the case specific boundary conditions. In addition, a short-term vision of only one intervention cycle is insufficient, as it is desired to preserve monuments for several generations. For this reason, the consequences of successive intervention cycles have to be understood.

In this thesis, an approach is introduced that supports the formulation of a conservation aim and which can be used as guidance to evaluate whether a suggested intervention would be an improvement or not. The starting point hereby is to compare four different states of the historic concrete: the ideal state, the actual state, the expected state and the acceptable state of conservation. The proposed intervention should lead to a state better than both the actual and expected state of conservation without interventions. It is important to consider that not only technical aspects and measurable performance are compared, but also the consequences for the heritage values have to be discussed.

How can we balance the technical demands and the preservation of heritage values, when heritage values and durability issues originate in the same material properties?

Durability issues will not necessarily have a negative impact on the heritage values, as it was seen for example in the case of the earth retaining walls of the unfinished Groot Museum. First, it is necessary to understand the relationship between the heritage values and the state of conservation; then, it should be evaluated whether an intervention is required/desirable or not.

When an intervention is required, dilemmas can occur when heritage values and durability issues have the same material origin. Such a dilemma was present in the case of Fort Bezuiden Spaarndam, where degradation and heritage values have the same origin, leading to the loss of valuable historic material. In cases where no technical solution exists to preserve heritage values and to treat degradation, sufficient background information is necessary to make the best decision under the given circumstances. In order to solve such apparent dilemmas, it is relevant to understand the relationship between original material, the heritage values, and the ideal state and acceptable state, and to evaluate the impact of an intervention on both heritage values and treatment of degradation.

In reality, no perfect conservation strategy will exist that always allows preserving all heritage values whilst treating all degradation mechanisms. A realistic understanding of what is technically possible and the risks and benefits of different conservation strategies are hereby essential. A previously formulated conservation aim can give guidance. It can be justified why a technical optimal solution is not carried out or why some heritage values/functional aspects might have to be sacrificed in order to preserve other relevant aspects of the monument, or why accepting degradation would preserve more heritage values on the long-term. A solution has to be found which under the case specific boundary conditions offers the best option; again, the four states introduced in this thesis can be used as guidance.

It shall be clear that just fulfilling technical demands cannot be the only and main criterion for conservation. Likewise, a too strong emphasis on the preservation of heritage values will not guarantee their preservation as technically poor interventions can endanger both heritage values and material. Historic concrete will always undergo changes. A sound and realistic understanding of the actual and expected state of conservation is necessary, and an ideal state should be seen as what it is: a conceptual ideal state.

What is historic concrete? What are the specific properties and applications of historic concrete?

Understanding historic concrete is the foundation of any listing and conservation of built heritage involving this material. The current unawareness about the characteristics of historic concrete has led to one of the main unexpected side steps during this research, as no further discussion on how to preserve historic concrete was possible without understanding the material. Therefore, in Part I of this thesis, a reference work was compiled in order to give a first answer to these questions.

More research is necessary to answer these fundamental questions in detail, but what can be concluded is that historic concrete is much more diverse than usually assumed. It is not only a structural material, but a universal material, adapted to the situation in which it was used, varying for example from sewers, sculptures, façade elements, foundations, window sills to beams. As a historic material, it reflects both the development of concrete technology and its increasing application in different fields. As for any historic material, different historic periods with their own specific features can be identified. These features are reflected in many details, such as composition and used constituents, underlying design codes (if any), geometry, design and not at least the appearance of historic concrete.

Generalised statements on the properties of historic concrete cannot be made. However, for specific periods characteristics can be identified. In Section 2.3 *Historical context and material properties*, an overview was given of what can be expected from a historic concrete from a specific period in terms of used constituents and appearance. A common line is the growing insight into the design

and control of both structure and composition of concrete, in order to achieve the desired quality and durability.

With this thesis, common prejudices towards historic concrete were rebutted: the history of historic concrete is literally much more colourful than one usually thinks; the state of conservation of historic concrete buildings is not always poor, and concrete is a historic construction material of its own, deserving protection and to be considered of historic value.

What are the possible heritage values of historic concrete and how are they related to the historic concrete as a material?

Historic concrete itself is often denied the recognition of being historically valuable. Instead, the architectural and structural achievements made with concrete are honoured and concrete demeaned as an instrument. Especially the development of concrete technology is neglected; details are not understood, nor is it recognised that one concrete differs from another.

Another aspect commonly discussed is whether the existing sets of heritage values are applicable for historic concrete and 20th century architecture in general. Suggestions are to neglect some categories and to modify others. Arguments put forward are the increase appreciation of the design intent and the decrease of workmanship due to more industrialised construction methods. Understanding the properties of historic concrete, its technological development and increasing application, it can be concluded that no special heritage values have to be ascribed to historic concrete. Instead, the entire existing scope of heritage values should be considered, and discussed how they are reflected in historic concrete. It has to be accounted for that differences in interpretation of heritage values with previous periods do exist. For example, historic concrete is frequently denied the value of workmanship as it is considered a designed material and sometimes prefabricated and mass-produced. It has however to be understood that much of the development of historic concrete took place in laboratories and behind the office desk; prefabrication has to be seen as a modern method of workmanship and it has to be considered that within this field an evolution took place. The remaining historic concrete is therefore evidence of a new technological and scientific approach towards construction and material development.

Which properties of historic concrete affect its durability and therefore possibly the heritage values of the material?

First, it has to be understood that no concrete is everlasting, and material changes affecting its performance will always occur. Once it is recognised which material aspects represent the heritage values of a specific historic concrete (structure), it can be case specifically discussed which heritage values are affected by the present degradation.

However, the historic concrete encountered in monuments dates often from the pioneering phase of concrete technology, a phase with little insight into durability, regarding material composition, design details and construction. In some cases, this might have led to a concrete more vulnerable towards certain degradation types. For instance, the lack of mix design rules (for example grading, water content) in combination with previous compaction methods might have increased the risk of freeze-thaw damage or increased the depth and speed of the carbonation front due to the different microstructure. Previous design rules allowed the design of more slender elements, as the underlying durability problems related to carbonation induced corrosion and the role of the concrete cover were not known; buildings designed to these former rules might be appreciated for their proportions which however affected negatively the durability. Other examples are the aesthetical choices influencing the surface finish (for example, tooling reduced the cover thickness and affected the quality of the surface) might have decreased the durability, or less durable or even deleterious pigments might have been used to alter the colour. In addition, due to the age of the historic concrete, the risk of the appearance of time-dependent damage mechanisms may have increased.

Heritage values related to historic concrete, such as for example values related to technological development, workmanship, aesthetics or age might be more commonly affected by degradation than intangible heritage values. As proposed in this thesis, it is relevant to understand the mutual relationship between heritage values, historic concrete and state of conservation to evaluate whether present degradation is either a threat, an expression of heritage values or indifferent towards the heritage values.

Which are the limitations of present concrete conservation/repair approaches/techniques?

Conservation of historic concrete is a recent field, and an initial question was whether the techniques used for conservation are adequate or if it is necessary to develop new or modify existing techniques. In the several cases studied, the performance of repairs was not satisfactory; the causes are most likely related to insufficient pre-investigation, leading to the choice of an unsuitable repair technique, and/or due to poor workmanship.

In conservation practice, one of the main limitations is the lacking background information on historic concrete and its repair in general. Sufficient reference material to characterise historic concrete and to evaluate the risks and benefits of an intervention is not available. The specific requirements of concrete conservation still have to be formulated more systematically, indicating which aspects need modification, both from conceptual and technical points of view. Only when the demands of concrete conservation are clearly formulated, existing repair techniques can be critically reviewed and current limitations identified. The information given in Part I of this thesis regarding the properties of historic concrete and in

Chapter 9 *Impact of repairs on historic concrete and heritage values* can be used as a starting point.

In practice, it has to be understood that more detailed, case specific research is necessary to develop compatible repair materials. It is a common phenomenon that repair techniques are chosen without identifying the properties of the historic concrete, underlying causes of damage, and risks or benefits of an intervention. The use of proprietary repair materials without critical reflection is still too common. An adaptation in colour is hereby not sufficient. Two examples which would require further investigation are the repair of *brikkenbeton*, made with trass-lime binder and broken bricks, and the repair of the coloured concrete using a variety of aggregate and surface finishes as encountered in the works of H.G.J. Schelling.

12.1.3 Discussion of results

The main aim of this research was to improve the current and future practice of conservation of historic concrete. With this thesis, an approach is suggested in order to formulate a dedicated conservation strategy, consisting of three main phases, each represented in one part of this thesis.

Part I Understanding and Characterisation of Historic Concrete

Part I offers background information to support the understanding and characterisation of historic concrete, addressing the different knowledge gaps regarding historic concrete in the Netherlands. The developed reference work focuses on the material and explains the historical context, including the former state-of-the-art, application and appreciation of historic concrete. With the offered information, the investigation of historic concrete in the Netherlands can be improved, allowing a better formulation of hypotheses regarding the properties of a concrete from a specific period.

The given information is relevant for technical evaluations, historical surveys and value assessments likewise, as the historic concrete can be better characterised. Subsequent decisions and interpretations can be made, based upon an increased understanding of the material and its historical context. The perception of the variety of heritage values applicable for historic concrete should be influenced, as heritage values related to building technology, scientific development and workmanship can be identified more systematically; values which have been frequently neglected for historic concrete.

The first part of this thesis has an educative function as well, explaining the material history of historic concrete, including obsolete terminology. It is not restricted to listed monuments and can be applied for other concrete buildings dating from the period investigated (late 19th century to 1960s), as the information on the material composition, mix design rules and previous understanding of durability can be relevant in a normal repair context. The increasing interest in the repair of

the existing infrastructure, most of which was built after the Second World War, is only one example where detailed information on historic concrete is relevant.

Although the investigation focused on the Netherlands, the given information can be used to a certain degree for other countries. The main developments took place in parallel, with possible slight time shifts, depending on the level of sophistication of the country in question. Local preferences regarding raw materials used have to be considered, the same applies for the introduction of standards and codes of practice. However, the given information cannot replace the historical context of other countries, which is relevant for value assessments.

Part II Interpretation and Evaluation of Historic Concrete

In Part II, the present day situation of historic concrete was discussed. The main focus lay on the way historic concrete is interpreted and evaluated, as such discussions lead to conclusions on whether an intervention is necessary or not, and on its possible characteristics. During this phase of the conservation process, a strong dominance of concrete repair approaches was noticed, whose aims diverge from those of conservation. A main concern is that discussions related to heritage values and those on the state of conservation are commonly carried out separately, and heritage values seldom considered when taking technical decisions. To integrate systematically the preservation of heritage values as an equal criterion during technical discussions, it is necessary to translate them into material related attributes. This is essential, as changes initiated by degradation and intervention will affect the heritage values through the material, either positively, negatively or indifferently.

In this part, an approach was suggested to relate the heritage values to the historic concrete, and to evaluate material changes considering the historical context during construction and the history of the building in service. By understanding the mutual relationship between heritage values, historic material and state of conservation, conclusions can be drawn on whether heritage values are endangered, as interventions should not only be carried out when the technical performance or functionality is at risk but also when the heritage values are.

In order to sharpen the interpretation and evaluation of historic concrete, and the way decisions are made regarding interventions, the differences between concrete conservation and concrete repair - two fields that are often intermingled in practice - had to be clarified first (see Section 12.1.1). By understanding the diverging aims and criteria of the two fields, it became clear that decisions on whether interventions are necessary should not be made solely on technical aspects, but equally influenced by the endangerment and preservation of heritage values. To improve the conservation of historic concrete, an approach has been introduced to translate conceptual demands such as preserving a specific heritage value into material related attributes, which should be understandable for the involved parties.

Part III Development and Evaluation of a Dedicated Conservation Strategy

In Part III, the previously obtained information and analyses are combined for the development of a dedicated conservation strategy. Based on the outcomes of Parts I and II, an approach is suggested which allows the formulation of case specific criteria for the development and evaluation of different conservation strategies. As each conservation project is different, no universal advices for specific material groups can be given. Instead, for each conservation project case specific boundary conditions and criteria have to be developed based on the conservation aim to which potential conservation strategies can be evaluated. A major challenge lies here in translating conceptual demands such as preserving a specific heritage value into material related attributes. A prerequisite is a detailed understanding of the historic concrete, its historical context and its properties. Equally important is to address which degradation mechanisms and symptoms have to be treated and which can be accepted.

Before discussing which technique would be suitable, it is necessary to come to a mutual agreement on the conservation aim, clarifying in which physical state the historic concrete would transfer its ascribed heritage values the best and outlining demands towards the usability of the structure. In order to develop the conservation aim, four different states of the historic concrete were introduced in Chapter 10: the actual state, the expected state, the ideal state and the acceptable state of conservation. An analysis of the relationship between these four states allowed the formulation of case specific criteria for a conservation strategy.

These criteria are the starting point to characterise the properties of possible conservation strategies. Proposed conservation strategies can be evaluated using once again the previously introduced four states of conservation. Part of the conservation aim is to improve the actual and expected state of conservation in case they are too close or even below the acceptable state of conservation, and to create a state that is closer to the ideal state. Interventions should not only lead to situations better than the acceptable state but in addition remain above the expected state of conservation. Otherwise, the benefit of conservation treatment can be questioned.

Case studies

As shown in the three case studies used in Parts II and III, decisions were based upon both preservation of heritage values and technical demands. The case studies varied in underlying cause of damage, type of historic concrete and ascribed heritage values, resulting in different conservation aims. The conservation aim gave guidance on whether interventions were necessary. The specific aspects were that solutions not solely focussed on the treatment of causes of damage or symptoms. Instead, threats related to both technical aspects and heritage values, which caused divergence from the ideal state, were considered. The developed criteria for the

case studies helped to identify suitable repair principles and their necessary adaptations. In practice, detailed research on the properties of a repair technique would be still necessary, including its composition (e.g. repair mortars), compatibility, application, reversibility or retreatability, and durability.

When comparing the outcomes of the studied cases to a possible state of conservation, which would have been likely when only following a repair approach, a shift of emphasis can be noticed. Not the treatment of a cause of damage is the main aim, but the maintenance or improvement of the expected state of conservation, allowing a state that would be closer to the ideal state. This includes the consideration of the impact of interventions on both the original material and the ascribed heritage values. The perpetual heritage service life is reflected by addressing the long-term impact of an intervention and by considering several intervention cycles (for example failure, removal, retreatability). The emphasis to preserve the original material is reflected in choosing more sensitive techniques, which allow a better control during application (e.g. cleaning) or failure (e.g. localisation of loss of bond of a repair mortar).

As repeatedly addressed, the conservation aims and material properties of historic concrete vary, questioning if the outcomes of the proposed cases are transferable to other situations. A judicious neglect as suggested for the unfinished earth retaining walls of the Groot Museum might not be applicable in cases where the monument has to remain functional and fulfil regular safety demands. The acceptance of further, yet decelerated degradation as suggested for Fort Bezuiden Spaarndam might be appropriate in other cases. However, one technical advantage of the fort is that it is not reinforced and that therefore common safety problems related to corrosion are not relevant. The Hofplein railway viaduct, on the other hand, reflects more common problems related to corrosion and endangerment of the original surface.

So, which situations and dilemmas would be more commonly encountered? From the buildings evaluated during this research (Appendix B *Overview of visited objects*), insight into the properties of historic concrete and studied literature, a common problem is corrosion caused by an insufficient concrete cover, often in combination with a poor concrete quality. Limitations for repair are either geometrical restraints, which might exclude an increase of the cover, or valuable surfaces, which should be kept in place. Surprisingly, the reinforcement, which is always affected during corrosion, is generally only seen as the initiator of damage but not as a historically valuable material that should be kept. If one would apply the four states of conservation to such cases and develop a conservation aim, what would that be? Independently of the case, the on-going corrosion would cause a loss of surface, geometry, reinforcement and finally of function. Case specifically, the heritage values associated to these aspects would be lost.

Depending on the monument, it should be decided which material aspects related to the heritage values should be protected. This requires a case specific ideal state of conservation. To develop a dedicated conservation strategy, it should be understood what is achievable and which losses have to be accepted (incorporated

in the accepted state of conservation). In case the preservation of the original reinforcement is the main aim, (local) loss of the surface and of the concrete may be considered in order to install a preventive technique. The same is applicable when not (only) the reinforcement but also the original concrete and/or surface are valuable and endangered. A local loss of the valuable surface/concrete may have to be accepted in order to apply preventive measures and preserve as much as possible on the long-term. Comparing different conservation strategies should show the relationship between the quantity of material removal, the number of repair cycles during a specific period (and necessary material removal during each cycle) and overall material loss.

In practice, the approach proposed in this thesis would require all parties to discuss and make mutual agreements considering the impact and benefits on both technical performance and preservation of heritage values. This demands discussions and decisions on successive maintenance and repair cycles, a relevant aspect considering the perpetual heritage service life. In practice, this is most often not carried out. Detailed pre-investigations are encouraged as the need of detailed information for the decision-making process is shown, including support for interdisciplinary investigations. For implementation and further education of the field, detailed guidelines and reference works focusing on historic concrete and its conservation, addressing different damage mechanisms, methods of investigation, material properties and required properties of repair techniques are still necessary.

With the suggested approach, heritage values will become understandable for the different parties involved in the conservation of concrete. It allows a systematic integration of technical demands and the preservation of heritage values in the conservation process, and offers the required background knowledge on historic concrete and repair techniques. Guidance is given on the formulation and application of case specific criteria for a dedicated conservation strategy. The results of this thesis help to initiate the development of concrete conservation as an own discipline, and not a makeshift solution using technical components from concrete repair and fragmented knowledge based on randomly selected historic concrete buildings and textbooks.

The approach described in this thesis is not limited to historic concrete, but can be applied in theory to different historic materials and different types of interventions. A prerequisite is sufficient background information allowing the identification of the four different states of the historic concrete and the formulation of the conservation aim. In most cases, an ideal state cannot be reached; however, improvements can be evaluated by comparing expected states of conservation with and without intervention, and determining case specific benefits and threats.

Conservation of historic concrete, which considers both technical demands and the preservation of heritage values is possible but requires specific knowledge by the heritage specialists involved, and sufficiently profound scientific data regarding the historic concrete of the conservation project in question and concrete conservation techniques.

12.2 Further research and recommendations

Further research regarding the conservation of historic concrete is required, both scientific and related to methods to implement and disseminate the gained knowledge in practice.

In Part I, a first generic reference work for material aspects of historic concrete in the Netherlands was compiled. Direct results of this research were the identification of the different development phases of concrete in the Netherlands with their specific material properties and of Dutch characteristics, and a clarification of (obsolete) terminology. As the main information sources were textbooks, journal papers, and data from site visits, sometimes supported by material samples, more evidence for the application and possibilities of identification is desired, including the influences on degradation and consequences for repair materials.

Material and construction historical aspects that have not been discussed include (prefabricated) building elements (e.g. foundations, floor elements), calculation and development of theories, concrete companies, concrete masonry bricks, pre-fabricated concrete, pre-stressed concrete, and construction methods. Special aspects would be the emerging of plain concrete during the 19th century, and the specific constituents used. Another aspect that has not been fully understood yet is why the Netherlands became one of the leading countries for using *hoogoven cement* (blast furnace slag cement) for marine structures in the 1930s, whereas in the 1920s the Dutch still had strong prejudices against this cement. Of international interest would be to understand the international trading with raw material, including the export of Dutch trass for early plain concrete structures, and to compare the imported and exported raw materials with other countries, both in terms of historical information, material properties and experience with conservation.

The current limitations of concrete repair techniques have been previously mentioned in Section 12.1.2 *Reflecting the research questions*. For a better understanding, a focused investigation and evaluation of repair techniques used for historic concrete, which fulfill requirements of conservation, should be carried out. This includes the evaluation of the performance of repairs of historic concrete in the field, and determining the underlying causes for success and failure. With an increasing insight into the properties of historic concrete and the specific criteria for conservation, research could be carried out to develop more suitable conservation techniques, if these appear to be necessary.

In practice, the level of investigation and effort during repair has to be chosen in accordance with the importance of the historic concrete and the severity of the encountered damage. As concrete conservation is still a recent field, extra care has to be taken. Previous repairs of historic concrete buildings can only be used limitedly as reference projects as in most cases the intervention was carried out as repair and not as conservation, and the preservation of heritage values not addressed. Therefore, with the different premises between repair and conservation, and the deviating properties of historic concrete compared to present day concrete,

additional, even fundamental, research might often be required. The underlying complexity of concrete conservation and the properties of historic concrete have to be disseminated more amongst restoration architects, owners, contractors and authorities.

In order to improve the practice of concrete conservation, knowledge on historic concrete in all fields related to conservation of historic concrete needs to be disseminated. This includes an interdisciplinary training of conservation specialists addressing construction history, durability, and conservation techniques. The interdisciplinary character must be enforced in conservation practice and experts have to be aware of the limits of their own expertise and the understanding when it is necessary to consult other experts. In order to make mutual agreements on conservation aims and a dedicated conservation strategy, a broader knowledge and understanding of the involved disciplines is essential.

Systematic documentation of interventions, underlying motivations and execution in a general database is recommended for several reasons. First, for future repairs, information would be available on the repair techniques used, the underlying cause of damage and conservation aim, and complications during execution. By this, future interventions could profit from previous experience, and the technical performance better evaluated. Complications arising from repair materials previously used could be indicated and research better directed. The effectiveness of an intervention could be predicted better and a repetition of the same mistakes avoided.

On a wider scale, the collected data could help to increase our knowledge of suitable conservation techniques and indicate reoccurring problems within the field of concrete conservation. This requires a uniform reporting format indicating the intention of the intervention, the treated symptoms and causes, the used methods and materials, the expectations, obstacles during execution, and an updating of the data with inspection reports on performance and failure of interventions. Such a database is not only necessary for historic concrete but for the entire field of conservation, as too often only information on functional and design changes, or legal and contractual aspects are archived.

12.3 Final conclusions

Historic concrete buildings were not designed with the intention to last forever, and no repair techniques exist which can guarantee a perpetual heritage service life. However, attempts should be made to preserve a historic concrete monument with its heritage values related to the original structure and material for as long as possible. At the time of listing, many concrete structures are 50 years and older, usually an age when many concrete structures face the end of their designed service life. In addition, it is not uncommon that historic concrete monuments faced periods of neglect and vacancy, speeding up degradation, and thereby offering additional challenges for conservation.

Preserving a historic concrete building is not only about aesthetics and for stretching a service life beyond what might seem to be economically or technically reasonable, instead an entire new framework is to be set. Repair approaches, which are now often uncritically applied for conservation, must be reconsidered in order to allow to design a heritage service life, which combines preservation of heritage values and extended service life.

Part of the reconsideration process must be that historic concrete has to be understood as a historic material with accompanying heritage values and not only as a structural material. Concerning the perpetual heritage service life, evaluation and comparison of successive intervention cycles must be performed. Limited knowledge and experience with conservation of historic concrete makes such a prediction still difficult. Choices have to be made carefully, as most repair techniques are neither designed nor field-tested for historic concrete; specific conservation techniques and specialist barely exist.

Conservation of historic concrete always requires case specific approaches, as for each object not only the material can differ, but also heritage values and the conservation aims. Last but not least, when working with historic concrete one should be prepared that once knowing and understanding historic concrete, its history and properties can be much more detailed and complex than one would think, and that there is much more (to) historic concrete than one would initially expect.

Part IV

Appendices

Appendix A

Obsolete concrete terminology (English, Dutch, German)

In this appendix, a trilingual overview is given of obsolete concrete terminology. In order to facilitate the consultation of historic textbooks in different languages and to respect the different connotations, a comparison of English, Dutch and German terms is given. Hereby, the main focus lies on the Dutch obsolete terminology; example references indicate the period of use.

Especially at the beginning of the 20th century, a wider variety of terms and of possible translations can be found. Due to the pioneering phase of the field and the lack of standards, misinterpretation in original historic documents cannot be excluded, including the translation of foreign words into Dutch and vice versa. The presented list is not exhaustive, and focuses on the main topics of Part I *Understanding and Characterisation of Historic Concrete*.

Glossary

Aggregates .

- 1) **Toeslag** Dutch.
- 2) **Steengruis** Dutch, see Van der Kloes et al. (1924).
- 3) **Zuschläge** German.
- 4) **Magerungsmittel** German, see Burchartz et al. (1927).
- 5) **Steingrus** German, see Van der Kloes (1913).

All-in aggregate .

- 1) **Grit** English.
- 2) **Gravelous sand** English.
- 3) **Grindzand** Dutch, see Betonvereniging (1929); Boon (1908, 1913, 1920, 1931); Van der Kloes et al. (1923).

- 4) **Grindmateriaal** Dutch, see Betonvereniging (1929).
- 5) **Grobsand** German.
- 6) **Kiessand** German, see Kersten (1907a).

Bar iron , see Van der Kloes et al. (1925).

- 1) **Staafigzer** Dutch, see Van der Kloes et al. (1925).
- 2) **Stabeisen** German, see Van der Kloes et al. (1925).

Bars in angles and tee sections .

- 1) **Profielijzer** Dutch, see Koninklijk Instituut van Ingenieurs (1911).
- 2) **Formeisen** German, see Koninklijk Instituut van Ingenieurs (1911).

Blast furnace slag cement .

- 1) **Portland Blast furnace slag cement** English, when clinker and blast furnace slag are interground, see Lea & Desch (1935).
- 2) **Hochofen cement** English, see Lea & Desch (1935).
- 3) **Hoogovencement** Dutch.
- 4) **Hochofenzement** German.
- 5) **Montanzement** German, see Van der Kloes (1913).
- 6) **Montan cement** English, see Van der Kloes (1914).
- 7) **Blast furnace slag cement** English, see Van der Kloes (1914).

Boiler slag .

- 1) **Ketelslakken** Dutch, see Scharroo (1942b).
- 2) **Kesselschlacke** German, see Probst (1935).

Breeze concrete , see Hurst (2001); Friedman (2010).

- 1) **Cinder concrete** English, see Hurst (2001); Friedman (2010).
- 2) **Korrelbeton** Dutch, see Scharroo (1946).
- 3) **Slakkenbeton** Dutch, see Bergsma & Homan van der Heide (1910b); Van der Kloes et al. (1924).
- 4) **Sintelbeton** Dutch, see Bergsma & Homan van der Heide (1910b); Van der Kloes et al. (1924).
- 5) **Kolenslakkenbeton** Dutch, see Bergsma & Homan van der Heide (1910b).
- 6) **Schlackenbeton** German, see Kersten (1907a).

Broken bricks .

- 1) **Brickyard refuse** English, see Reid (1869).
- 2) **Brikken** Dutch, see Van der Kloes (1893).

Bush hammering .

- 1) **Bouchaderen** Dutch, see Scharroo (1946).
- 2) **Stocken** German.
- 3) **Bouchardieren** German.

Cast iron .

- 1) **Gietijzer** Dutch, see Van der Kloes et al. (1925).
- 2) **Gußeisen** German, see Memmler et al. (1907).

Chiseling, special pattern .

- 1) **Kathedraalslag** Dutch.

- 2) **Kreuz- und Querschläge scharrieren** German, see Petry (1913).

Chiselling .

- 1) **Scharreren** Dutch, see Scharroo (1946).
- 2) **Frijnen, frijnslag** (finer than scharrieren) Dutch, see Scharroo (1946).
- 3) **Scharrieren** German, see Petry (1913).

Coke breeze .

- 1) **Sintel** Dutch.

Concrete .

- 1) **Beton** English, see Reid (1869).
- 2) **Beton** Dutch.
- 3) **Grobmörtel** German, see Becker (1857); Van der Kloes (1893).

Concrete made with broken bricks as coarse aggregate .

- 1) **Brikkenbeton** Dutch, see Van der Kloes (1893).
- 2) **Ziegelbeton** German, see Memmler et al. (1907).

Confined reinforced concrete columns .

- 1) **Omweekt beton** Dutch.
- 2) **Umschnürte Stahlbeton-/Eisenbetonstütze** German.

Crushed rock .

- 1) **Steenslag** Dutch.
- 2) **Schotter** German, see Kersten (1907a).

Dry concrete , see Taylor & Thompson (1905).

- 1) **Aardvochtig beton** Dutch.
- 2) **Erdfeuchter Beton** German.

Early high strength Portland-cement , see Scharroo (1946).

- 1) **Cement met hoge aanvangsvastheid** Dutch, see Scharroo (1946).
- 2) **Edelcement** Dutch.
- 3) **Groenstreep cement** Dutch, see Scharroo (1946).
- 4) **Hochwertiger Zement** German, see Scharroo (1946).

Expanded metal inventor Golding.

- 1) **Plaatgaas** Dutch, see van Rossum (1902).
- 2) **Expanded metal** Dutch, see Boon (1908).
- 3) **Strekmetaal** Dutch, see Boon (1920).
- 4) **Metaalgaas** Dutch, see Scharroo (1916).
- 5) **Streckmetall** German, see Memmler et al. (1907).

Facing concrete .

- 1) **Facing layer** English, see Marsh (1904).
- 2) **Voorzetbeton** Dutch, see Wattjes (1931).
- 3) **Afwerklaag** Dutch, see Verhey (1912).
- 4) **Afwerkbeton** Dutch, see Van der Schrier (1938); Verhey (1912).
- 5) **Bekleedingsbeton** Dutch, see Muller (sa).
- 6) **Sierbetonlaag** Dutch, see Bergsma (1934).

- 7) **Edelbeton** Dutch.
- 8) **Vorsatzbeton** German, see Petry (1913); Von Mecenseffy (1911).

Gravel .

- 1) **Grint, grind** Dutch.
- 2) **Kies** German.

Ground granulated blast furnace slag .

- 1) **Slag sand** English.
- 2) **Slakkenzand** Dutch, see Van der Kloes (1911a,b).
- 3) **Hochhofenschlackensand** German, see Foerster et al. (1912).

Ground slag sand .

- 1) **Slakkenmeel** Dutch, see Van der Kloes (1913).
- 2) **Schlackenmehl** German, see Van der Kloes (1913).

High aluminum cement , see Neville (2008).

- 1) **High-aluminium cement** English, see Bogue (1947); Davey (1961); Lea & Desch (1935).
- 2) **Aluminous cement** English, see Bogue (1947); Lea & Desch (1935).
- 3) **Aluminiumcement** Dutch, see Betonvereniging (1929); Van der Schrier (1951).
- 4) **Alcement** Dutch, see Betonvereniging (1929); Van der Schrier (1951).
- 5) **Smeltcement** Dutch, see Betonvereniging (1929); Van der Schrier (1951).
- 6) **Ciment fondu** Dutch, see Betonvereniging (1929); Van der Schrier (1951).
- 7) **Electrocement** Dutch, see Van der Schrier (1951); van Dijk & Van der Baan (1952).
- 8) **Tonerdezement** German, see Probst (1935) van Dijk & Van der Baan (1952),.
- 9) **Ciment fondu** German, see Probst (1935).
- 10) **Ciment electrique** German, see Probst (1935).

Ingot iron .

- 1) **Steel** English, see Koninklijk Instituut van Ingenieurs (1900,1911).
- 2) **Vloeiijzer** Dutch, see Koninklijk Instituut van Ingenieurs (1911); Van der Kloes (1908c); Van der Kloes et al. (1925); Van Hemert (1901); Bergsma & Homan van der Heide (1910b); Van der Kloes (1908c, 1911a); Van der Kloes et al. (1925).
- 3) **Smeltijzer** Dutch, see Bergsma & Homan van der Heide (1910b); Boon (1908); Koninklijk Instituut van Ingenieurs (1900); Van der Kloes (1908c, 1911a); Van der Kloes et al. (1925).
- 4) **Flusseisen** German, see Kersten (1907a); Koninklijk Instituut van Ingenieurs (1911); Memmler et al. (1907); Van der Kloes (1908c); Van der Kloes et al. (1925).
- 5) **Flussstahl** German, see Koninklijk Instituut van Ingenieurs (1911).
- 6) **Schmiedeeisen** German, see Memmler et al. (1907).

Ingot steel .

- 1) **Vloeistaal** Dutch, see Van der Kloes (1908c); Van der Kloes et al. (1925); Van Hemert (1901);.
- 2) **Smeltstaal** Dutch, see Van der Kloes (1908c); Van der Kloes et al. (1925).
- 3) **Flussstahl** German, see Van der Kloes (1908c); Van der Kloes et al. (1925).

Iron-ore cement , see Bogue (1947); Lea & Desch (1935); Neville (2008).

- 1) **Erz cement** English, see Lea & Desch (1935).
- 2) **Erts-cement** Dutch.
- 3) **Erzzement** German, see Ast (1907); Bogue (1947); Memmler et al. (1907).
- 4) **Eisenzement** German, see Ast (1907).
- 5) **Ore cement** English, see Van der Kloes (1914).

Kahn iron .

- 1) **Kahn ijzer** Dutch, see Boon (1920).
- 2) **Kahnsche Eisen** German, see Memmler, et al. 1907.

Natural cement .

- 1) **Natuurcement** Dutch.
- 2) **Naturzement** German, see Probst (1917).

Pit gravel .

- 1) **Berggrind** Dutch, see Scharroo (1924).
- 2) **Grubenkies** German, see Probst (1917, 1935); Scharroo (1924).

Plain reinforcing bars .

- 1) **Glad rond betonstaal** Dutch, see Commision des Communautés Européennes (1974).
- 2) **Glatte runder Betonstahl** German, see Commision des Communautés Européennes (1974).

Portland cement .

- 1) **Portlandcement** Dutch.
- 2) **Portlandzement** German.

Portland slag cement , see Memmler et al. (1907).

- 1) **Slag-cement** English, see Memmler et al. (1907).
- 2) **Eisen Portland cement** English, see Lea & Desch (1935).
- 3) **Ijzerportlandcement** Dutch, see Scharroo (1946).
- 4) **Portland-slakken cement** Dutch, see Van der Kloes (1900).
- 5) **Eisenportlandzement** German, see Memmler et al. (1907) Scharroo (1946).
- 6) **Iron Portland cement** English, see Van der Kloes (1914).

Pozzolana cement , see Bogue (1947).

- 1) **Puzzolan- Zement** German, see Memmler et al. (1907).

Pumice .

- 1) **Puimsteen** Dutch, see Van der Schrier (1938, 1942).
- 2) **Bims** Dutch, see Van der Schrier (1938, 1942).

- 3) **Bims gruis** Dutch, see Van der Schrier (1938, 1942).
- 4) **Bimsstein** German.
- 5) **Bims** German.

Reinforced concrete .

- 1) **Ferro concrete** English, see Onderdonk (1928).
- 2) **Betonijzer** Dutch, see Dwars (1912); Scharroo (1910a).
- 3) **Cement-ijzer** Dutch, *also* cementijzer, see Sanders (1907); Scharroo (1910a).
- 4) **Armierter Beton** German, see Van der Kloes (1913).
- 5) **Eisenbeton** German, see Burchartz et al. (1927); Christophe (1905); Forster et al. (1908); Kersten (1907a,b); Probst (1917); Von Emperger (1904); Von Mecenseffy (1922).
- 6) **Stahlbeton** German since 1943.

Reinforcement, obsolete terms for .

- 1) **Armatuur** Dutch, see van Rossum (1902).
- 2) **Armierung** German, see Memmler et al. (1907).

River gravel .

- 1) **Rivier grind** Dutch.
- 2) **Flusskies** German, see Probst (1917).

Roman cement .

- 1) **Natural cement** English, see Memmler et al. (1907).
- 2) **Roman cement** Dutch, see Scharroo (1946).
- 3) **Romeinsch cement** Dutch, see Scharroo (1946).
- 4) **Romanzemente** German, see Memmler et al. (1907).

Round bars .

- 1) **Rond ijzer** Dutch, see Van der Kloes et al. (1925).
- 2) **Rundeisen** German, see Van der Kloes et al. (1925).

Slag cement , see ACI (1990); Lea & Desch (1935); Taylor & Thompson (1905).

- 1) **Slag-lime cement** English.
- 2) **Lime-slag cement** English, see Bogue (1947).
- 3) **Cold process slag cement** English, see Lea & Desch (1935).
- 4) **Slakkencement** Dutch.
- 5) **Pozzulaan cement** Dutch, see Van der Kloes, 1893.
- 6) **Schlackenzement** German, see Probst (1917); Van der Kloes (1913).
- 7) **Puzzolancement** German, see Huberti (1964); Van der Kloes (1913).
- 8) **Schlackenbinder** German, see Davey (1961).

Strips .

- 1) **Flat steel strips** English.
- 2) **Universalijzer** Dutch, see Koninklijk Instituut van Ingenieurs (1911).
- 3) **Flacheisen** German.

Supersulfated cement .

- 1) **Gesulfateerd cement** Dutch.
- 2) **Sealithor cement** Dutch.

- 3) **Gipsschlackenzement** German.
- 4) **Sulfathüttenzement** German, see Davey (1961); Wendehorst, 1949.

Tampered concrete .

- 1) **Stampbeton** Dutch.
- 2) **Stampfbeton** German.

Trass , see Davey (1961); Probst (1935); Vicat (1837).

- 1) **Dutch tarras** English, see Davey (1961); Probst (1935); Vicat (1837).
- 2) **Dutch terrace** sic, English, see Pasley (1838).
- 3) **Audenack tarras** English, see Vicat (1837).
- 4) **Trass cement** English, see Bogue (1947).
- 5) **Trass** Dutch.
- 6) **Trass** German.

Weld iron , see De Bouw (2010); Van der Kloes et al. (1925).

- 1) **Wrought iron** English, see De Bouw (2010); Koninklijk Instituut van Ingenieurs (1911).
- 2) **Welijzer** Dutch, see Koninklijk Instituut van Ingenieurs (1911); Van der Kloes (1908c); Van der Kloes et al. (1925); Van Hemert (1901).
- 3) **Schweisseisen** German, see Koninklijk Instituut van Ingenieurs (1911); Memmler et al. (1907); Van der Kloes (1908c); Van der Kloes et al. (1925),.
- 4) **Flussstahl** German, see Koninklijk Instituut van Ingenieurs (1911).

Weld steel , see Van der Kloes (1908b); Van der Kloes et al. (1925).

- 1) **Welstaal** Dutch, see Van der Kloes (1908c); Van der Kloes et al. (1925).
- 2) **Schweisstahl** German, see Van der Kloes (1908c); Van der Kloes et al. (1925).

Welded wire mesh .

- 1) **Baustahlmatten** Dutch, see Van der Schrier (1938).
- 2) **Betonstaalmatten** Dutch, see Gantvoort (1964); Van der Schrier (1938).
- 3) **Baustahlgewebe** Dutch, see Scharroo (1946); Van der Schrier (1938).
- 4) **Draadgaas** Dutch, see Anon. (1932b); Van der Schrier (1938).
- 5) **Staaldraadgaas** Dutch, see Anon. (1932b).
- 6) **Baustahlgewebe** German, see Probst (1935).

Wet concrete , see Taylor & Thompson (1905).

- 1) **Mushy concrete** English, see Taylor & Thompson (1905).
- 2) **Plastischer Beton** German.
- 3) **weicher Beton** German, see Ast (1907).
- 4) **Plastisch beton** Dutch.

Appendix B

Overview of visited objects



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(.2)



(.3)



(.4)



(.5)



(.6)



(.7)



(.8)



(.9)



(.10)



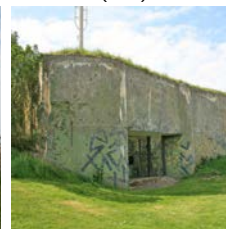
(.11)



(.12)



(.13)



(.14)

Military buildings 1) Fortification Hellevoetsluis, concrete elements built from 1880 onwards. **Stelling van Amsterdam, UNESCO World Heritage Site** 2) Fort near Vijfhuizen, 1899; 3) Fort Bezuiden Spaarndam, 1897-1901; 4) Fort Benoorden Spaarndam, 1901; 5) Fort near Aalsmeer, 1904; 6) Fort near Hooftdorp, 1904; 7) Bombproof shelters near Fort Bezuiden Spaarndam, ca. 1918; 8) Bombproof shelters near Fort Bezuiden Spaarndam, ca. 1918, model 1918; 9) Bombproof shelters near Fort Bezuiden Spaarndam, ca. 1918, model 1918; 10) Bombproof shelters near Fort Benoorden Spaarndam, ca. 1918; **Stelling Kornwerderzand** 11) Zoeklichtkazemat 7, 1932; 12) Commadokazemat 4; 13) Kazemat V 1933; 14) Kanonkazemat 6, 1932.



(.15)



(.16)



(.17)



(.18)



(.19)



(.20)



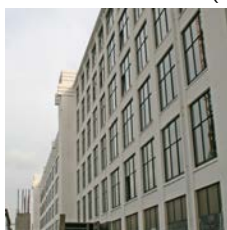
(.21)



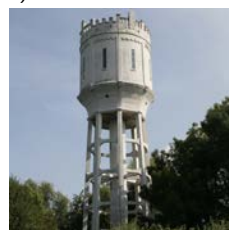
(.22)



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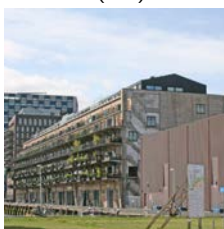
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15) Kazemat 14, 1933; 16) German Bunker, 1943. **Atlantic wall** 17) Hoek van Holland, bunker type 625b, built during WWII; 18) Hoek van Holland, bunker, built during WWII. **Civil buildings**
No regulation 19) Former office building Rotterdamsche Cementsteenfabriek van Waning & Co, Rotterdam, J. I. van Waning, 1898; 20) Former bank and office building Rijkspostspaarbank, Amsterdam, D. E. C. Knuttel, 1899-1901; 21) Hofplein railway viaduct, Rotterdam, A. C. C. G. van Hemert, 1900-1908; 22) Restaurant "De twee steden / Deux Villes", The Hague, 1904-1906, Joh. Muttters Jr.; 23) Factory building Calve factory (Moniergebouw), Delft, 1905; **Draft G.B.V 1909** 24) Former factory building N. V. Philipsgloeilampenfabriek (building EC), Eindhoven, A. Beltman, 1909-1911; 25) Water tower, Rijswijk, built by Koninklijke Rotterdamsche Betonijzer Maatschappij voorheen van Waning & Co., N. Biezeveld, 1911; 26) Intervention, Hotel De Rode Leeuw, Amsterdam, architect unknown, 1912; **G.B.V. 1912** 27) Circumambulation passageway Pilgrimage church, Brielle, H. Goossens (reconstruction), E.J. Margy, 1912; 28) St. Jobsveem, Rotterdam, J.J. Kanter, 1912.



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29) Rice silo for the Lassie factory, Wormerveer, architect/engineer unknown, 1912 30) Cenacle Church, Heilig Land Stichting, J. Stuyt, J. Margry, J. G. Wiebenga, 1913-1915; 31) Warehouse, Amsterdam, A. Joling, 1914 -1917; 32) Gerzon department store, Amsterdam, A. Moen, circa 1915; 33) Cacao factory Pette "Cacaotoren", Wormerveer, M. J. Stam, 1916; 34) Former Café La Reserve, Amsterdam, J. van Schaik, 1918; 35) Townhall Rotterdam, H.J. Evers and A.J.Th. Kok, 1914-1920. **G.B.V. 1918** 36) Former Faculty of Chemistry "Rode Scheikunde", TU Delft, G. van Drecht, 1918-1923; 37) Beton dorp Amsterdam, div. Architects 1918 -1928; 38) Façade refurbishment, Oudkerkhof, Utrecht, G. Rietveld, 1919; 39) Storehouse Mercurius, Wormerveer, M. J. Stam, 1919; 40) Former factory "Lichttoren" (building ED), Philips Eindhoven, Bureau TABROS, 1920-1921; 41) Former cotton warehouse (Katoenveem), Rotterdam, J. J. Kanter, 1920; 42) Westduin housing, Scheveningen, W. Greve, 1920-1922; 43) Unfinished Groot Museum Kröller - Müller, national park Hoge Veluwe, H. van de Velde, 1921-1922; 44) Radio Kootwijk, J. M. Luthmann, J. Emmen, 1921-22.



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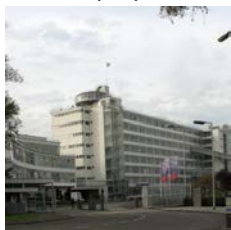
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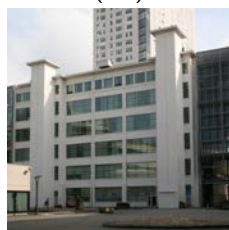
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45) Office building De Nederlanden van 1845, The Hague, H.P. Berlage, 1921-27; reconstruction 1945-47, extension 1954 by Dudok; 46) "Berlage" Kiosk, The Hague, H.P. Berlage and J. G. Wattjes, 1925; 47) Former Hypotheekbank, Noordeinde, The Hague, D. Roosenburg, 1925; 48) Housing Nirwana, J. Duiker and J. G. Wiebenga, 1925-1930; 49) Hotel, Amsterdam, G. J. Rutgers, G. van Arkel and H.J. Breman, 1925-1929; 50) Van Nelle factory, J.A. Brinkman and L.C. van der Vlugt, 1926-1931; 51) Former central garage, Koornmarkt, Delft, L. C. Kalis, 1926; 52) Foundations of the Hefbrug Koningshaven, Rotterdam, P. Joosting, 1927; 53) Water tower, Zutphen, H. Sangster, 1927-1928; 54) Office building "De Volharding", The Hague, J.W.E. Buijs and J.B. Luersen, 1927-1928; 55) Olympic stadium, Amsterdam, J. Wils, 1928; 56) "De Witte Dame", Eindhoven, 1928-1930; 57) Sanatorium Zonnestraal, Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928; 58) Dresselhuys pavilion, part of Sanatorium Zonnestraal, Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928.



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59) "Klokgebouw", factory building of Philipscomplex, Eindhoven, A. de Broekert, 1928-1929; 60) Atlantic house Rotterdam, P.G. Buskens, 1928-1930; 61) "Openluchtschool", school, Amsterdam, J. Duiker, 1929-1932; 62) Housing with shops, Utrecht corner Drift/Nobelstraat, exact date and architect unknown. **G.B.V. 1930** 63) HAKA - building, Rotterdam, H. F. Mertens, J. Koeman, 1931 - 1932; 64) "GEB toren" Rotterdam, J. Poot together with W.G. Witteveen and A.J. Steur, 1931; 65) Housing, Rotterdam, J.H. van den Broek, Th. ten Bosch, A. Otten, 1932; 66) Housing "Wolkenkrabber" Amsterdam, J. F. Staal, 1932; 67) Former dormitory for nurses, Delft, A. T. Kraan, 1932; 68) Housing, Walenburgerweg, Rotterdam, ca. 1933, architect unknown; 69) Monument Afsluitdijk, W. Dudok, 1933; 70) Social housing, Rotterdam, M. J. Granpré Molière and P. Verhagen, 1935; 71) Vocational school (Ambachtsschool), Zwolle, A. Baart & L. Krook, 1934; 72) Housing, Schepenstraat, Rotterdam, W. Th. ten Bosch, 1937.



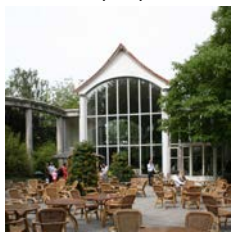
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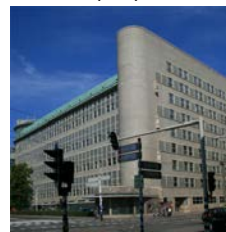
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73) Chabot Museum, 1938, G.W. Baas, addition 2nd floor 1976; 74) Main entrance, Zoo Blijdorp, Rotterdam, S. van Ravesteyn, sculptures L. Bolle, 1939-1941; 75) West wing of the "Rivierahof", Zoo Blijdorp, S. van Ravesteyn, 1939-1941; 76) Giraffe compound, Zoo Blijdorp, S. van Ravesteyn, 1940, sculptures L. Bolle; 77) Ventilation building for the Maastunnel, Rotterdam, J. P. van der Bruggen and A. van der Stuer, 1937 -1940; 78) Office building, The Hague, J. P. P. Oud, 1938-1946. **G.B.V. 1940** 79) Railway station post office, The Hague, G.C. Bremer, J. Emmen and H.J.J. Engel, 1939-49; 80) Exposition building Bouwcentrum, Rotterdam, J. W. C. Boks, 1946-48; 81) Office building, former Nationale Levensverzekering Bank, Rotterdam, A. A. van Nieuwenhuyzen, C. Elffers, 1941-1949; 82) Arrival hall of the Holland Amerika Lijn, Rotterdam, Brinkman, Van den Broek & Bakema, 1946 - 1949; 83) Bank building Twentsche Bank, Rotterdam, A. Van der Steur; W.A.C. Herman de Groot, B. Hooykaas, B. van Veen, A. de Jong, 1946; 84) Former office building and laboratory Dr. Neherlaboratorium, Leidschendam, S. J. van Embden, 1946-1955; 85) Housing Jerusalem Frankendaal, Amsterdam, B. Merkelbach, Ch. J. F. Karsten, P. J. Elling, 1947-1949; 86) Sculpture Prometheus, Amsterdam, F. Carraso, 1947.



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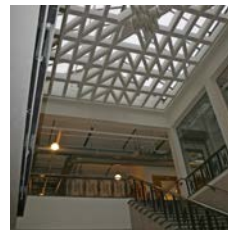
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87) School building "Grotius lyceum", The Hague, Sj. Schamhart, 1949-1955; 88) Commercial centre Lijnbaan, Rotterdam, Van den Broek & Bakema, 1949-1953. **G.B.V. 1950** 89) Office building Groothandelsgebouw, Rotterdam, H. Maaskant & W. van Tijen, 1950; 90) Railway station Enschede, H.G.J. Schelling, 1950; 91) Railway station Zutphen, H.G.J. Schelling, 1952; 92) Railway station Hengelo, H.G.J. Schelling, 1952; 93) Railway station Sonsbeekzijde Arnhem, H.G.J. Schelling, 1954, recently relocated; 94) Former workshop and storage building Las Palmas, van de Broek en Bakema, 1950-1953; 95) Provincial house (Huis der Provincie), Arnhem, J.J.M. Vegter and H. Brouwer, 1950-1954; 96) Office building Holbein huis, Rotterdam, H.A. & H. M. Kraaijvanger, 1951-1954; 97) School building, former Eerste Christelijke LTS Patrimonium, Amsterdam, J.B. Ingwersen, C. de Geus, 1952 - 1956; 98) Former Caballero factory (Laurens sigarette factory), The Hague, F.A.W. van der Togt, 1953; 99) Court house (Paleis van Justitie), Arnhem, F. Sevenhuysen Jr., 1953-1963.



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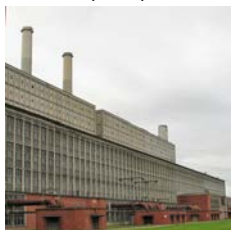
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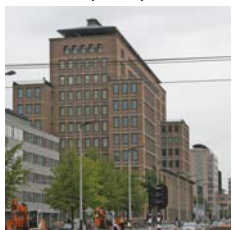
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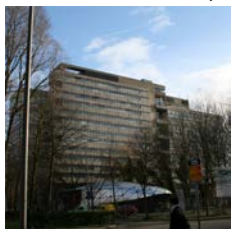
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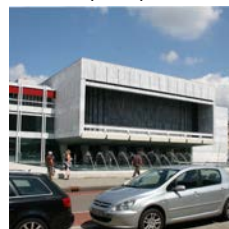
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100) Cultural / recreation area De Lichtenberg, P. Weegels, 1954-1961; 101) Thalia Theatre, Rotterdam, Bureau Hendriks, Van der Sluys & Van den Bosch, 1955; 102) Railway station post office, Rotterdam, E.H.A. & H. M. Kraaijvanger, 1954-1959; 103) Railway station post office, Arnhem, H. Engberts, 1955-61; 104) Office building and factory Harculo IJsselcentrale, Zwolle, P. J. de Gruyter, 1955; 105) Former tax office, Amsterdam, G. Friedhoff and M. Bolten, 1954-1958; 106) Housing Slotterhof, Amsterdam, J.F.Berghoef, 1958-1960; 107) Church St. Dominicus, Rotterdam, C. F. A. Knol / Office Kraaijvanger, 1958 - 1960; 108) Former orphanage, Amsterdam, A. van Eyck, 1959-61; 109) Aula TU Delft, Van den Broek & Bakema, 1958-68; 110) Observation tower Euromast, Rotterdam, H. A. Maaskant, 1960. 111) Pier Scheveningen, H. Maaskant, 1961; **G.B.V. 1962** 112) Faculty of Architecture, TU Delft, Van den Broek & Bakema, 1960-1970, burnt 13.05.2008; 113) Church, Opstandingskerk Voorburg, R. H. Fledderus, 1964; 114) Town hall, Arnhem, J.J. Konijnburg together with Ingenieursbureau Dwars, Heederik en Veerheij N.V., 1964-1968.



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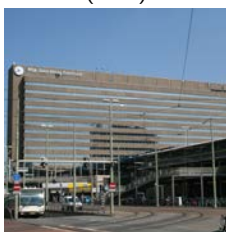
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115) Faculty of Civil Engineering, TU Delft, 1964-1975, van der Broek and Bakema; 116) Sculpture, TU Delft, C. Visser, 1966; 117) Church Thomaskerk, Amsterdam, K.L. Sijmons, 1966; 118) Pumping station Parksluizen, Rotterdam, G. J. van der Grinten, 1967; 119) Central station, The Hague, K. Gaast and J. van der Bak, 1968-1970; 120) Sculpture, Sylvette, Rotterdam, P. Picasso, 1970.

Appendix C

Overview of the different editions of
the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part A1)

G.B.V. 1912	G.B.V. 1918	G.B.V. 1930
Algemeene Bepalingen	Algemeene Bepalingen	Afdeeling I Algemeene bepalingen.
§1 Definitie	§1 -	§1 Aanduidingen van de voorschriften
		§2 Teekeningen
		§3 Ontwerp
Afdeeling I Materialen	Afdeling I Materialen	Afdeling II Materialen
§2 Cement	§2 Portlandcement	§4 Cement
§3 Zand	§3 Zand	§5 Zand
§4 Grind en Steenslag	§4 Grind en steenslag	§6 Grind en steenslag
§5 Beton	§5 Beton	§7 Water
§6 IJzer	§6 IJzer	§8 Samenstellen van het beton
		§9 IJzer

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part A2)

G.B.V. 1940	G.B.V. 1950	GBV 1962
Afdeeling I	Afdeling I	Afdeling I
Algemeene Bepalingen	Algemene Bepalingen	Algemene Bepalingen
§1 Aanduidingen van de voorschriften	§1 Aanduiding van de voorschriften	§1 Doelstelling en geldigheid
§2 Teekeningen	§2 Tekeningen	§2 Aanduiding
§3 Ontwerp	§3 Ontwerp	§3 Ontwerp en toezicht
		§4 Tekening en berekening
		§5 Afwijking van de voorschriften
Afdeeling II	Afdeling II	Afdeling II
Materialen	Materialen	Materialen
§4 Cement	§4 Cement	§6 Cement
§5 Zand	§5 Zand	§7 Zand
§6 Grind en steenslag	§6 Grind en steenslag	§8 Grind en steenslag
§7 Water	§7 Water	§9 Fijnheidsmodulus
§8 Samenstellen van het beton	§8 Samenstelling van het beton	§10 Water
§9 Staal	§9 Staal	§11 Hulpstoffen
		§12 Betonkwaliteiten
		§13 Samenstelling van het beton
		§14 Kubussterkte
		§15 Geschiktheidsproef, controleproef en verhardingsproef
		§16 Plasticiteit van betonspecie
		§17 Staal

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part B1)

G.B.V. 1912	G.B.V. 1918	G.B.V. 1930
Afdeeling II Uitvoering	Afdeeling II Uitvoering	Afdeeling III Uitvoering en constructie
§7 Personeel	§7 Personeel	§10 Personeel
§8 Stutten en formeelen	§8 Stutten en formeelen	§11 Opslag van materialen
§9 Aanbrengen van de wapening	§9 Aanbrengen van de wapening	§12 Bekisting. Werkvloer
§10 Voltooïing van de wapening	§10 Voltooïing van de wapening	§13 Aanbrengen van de wapening. Betondekking
§11 Het verwerken van het beton	§11 Het verwerken van het beton	§14 Bereiden en verwerken van beton
§12 Aan te sluiten oppervlakten.	§12 Aan te sluiten oppervlakten.	§15 Aan te sluiten van vlakken
§13 Afdekken en vochtig houden	§13 Afdekken en vochtig houden	§16 Afdekken en vochtig houden. In gebruik nemen
§14 Vriezend weer	§14 Vriezend weer	§17 Vriezend weer
§15 Minimum hoeveelheid ijzer, koppelingen en staafafstanden.	§15 Wegnemen van de bekisting	§18 Wegnemen van de bekisting Grindnesten
§16 Beproeving	§16 Gaten. Klossen. Richels.	§19 Gaten. Klossen. Latten enz.
	§17 Hoeveelheid ijzer. Koppelingen. Staafafstanden en betondekking .	§20 Wapening van platen
	§18 Beproeving	§21 Wapening van balken
		§22 Wapening van kolommen
		§23 Haken, ombuigen en lasschen van wapeningsstaven
		§24 Minimum vloerdikten
		§25 Beproeving. Vooraf klaargemaakte constructiedeelen

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part B2)

G.B.V. 1940	G.B.V. 1950	GBV 1962
Afdeeling III Uitvoering en constructie	Afdeling III Uitvoering en Constructie	Afdeling III Uitvoering
§10 Personeel	§10 Personeel	§18 Personeel
§11 Opslag van materialen	§11 Opslag van materialen	§19 Opslag van materialen
§12 Bekisting. Werkvloer	§12 Bekisting. Werkvloer	§20 Bekisting en werkvloer
§13 Aanbrengen van de wapening. Betondekking	§13 Aanbrengen van de wapening. Betondekking	§21 Aanbrengen van de wapening.
§14 Bereiden en verwerken van beton	§14 Bereiden en verwerken van beton	§22 Mengen en verwerken van betonspecie
§15 Aansluiten van vlakken	§15 Aansluiten van vlakken	§23 Aansluiten van vlakken
§16 Afdekken en vochtig houden. In gebruik nemen	§16 Afdekken en vochtig houden. In gebruik nemen	§24 Verharding
§17 Vriezend weer	§17 Vriezend weer	§25 Storten bij lage temperaturen.
§18 Wegnemen van de bekisting Grindnesten	§18 Wegnemen van de bekisting Grindnesten	§26 Ontkisten, grindnesten
§19 Gaten. Klossen. Latten enz.	§19 Gaten. Klossen. Latten enz.	§27 Gaten. Klossen. Latten enz.
§20 Wapening van platen	§20 Wapening van platen	Afdeling IV Constructie
§21 Wapening van balken	§21 Wapening van balken	§28 Dekking
§22 Wapening van kolommen	§22 Wapening van kolommen	§29 Haken en ombuigen
§23 Haken, ombuigen en lasschen van wapeningsstaven in op buiging belaste	§23 Haken, ombuigingen en lasschen van wapeningsstaven Minimum vloerdikten	§30 Verankeringslengte
§24 constructiedeelen	§24 Beproeving	§31 Lassen Algemeen
§25 Minimum vloerdikten	§25 Vooraf klaargemaakte constructiedeelen	Elektrisch lassen
§26 Beproeving Vooraf klaargemaakte constructiedeelen		Autogene lassen
		§32 Vloerplaten
		§33 Wanden
		§34 Balken
		§35 Kolommen
		Bebeugelde kolommen
		Omwikkelde kolommen
		Samengestelde kolommen

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part C1)

G.B.V. 1912	G.B.V. 1918	G.B.V. 1930
Afdeeling III Berekening	Afdeeling III Berekening	Afdeeling IV Berekeningen
§17 Definitie	§19 Definities en bepaling van het soortelijke gewicht.	§26 Berekening.
§18 Empirische regels	§20 Berekening	§27 Grondslagen voor de berekening
§19 Statisch onbepaalde constructiedelen	§21 Statisch onbepaalde constructies.	a. Definities
§20 Momenten	(Momenten)	b. Lengte van overspanningen en opleggingen
§21 Trek- en drukspanningen. Schuifspanningen	§23 Trek- en drukspanningen Schuifspanningen	c. Eigengewicht
§22 In ijzer en beton toe te laten spanningen.	§24 In ijzer en beton toe te laten spanningen	d. Belastingen
§23 Toe te laten spanningen bij overlegging van de uitkomsten van verrichte proeven	§25 Berekening van kolommen	e. T-balken
§24 Knikvastheid	§26 Knikvastheid	§29 Statisch onbepaalde constructies
§25 T-vormige balken	§27 Berekening van ongewapende kolommen	§30 Momenten. Dwarskrachten. Steunpuntreacties
	§28 Bijzondere constructies	§31 Inwendige spanningen
	§29 Aanduiding der voorschriften.	a. Buigspanningen (trek- en drukspanningen)
		b. Spanningen door dwarskrachten (schuine trekspanningen)
		c. Toe te laten spanningen
		§32 Berekening van kolommen
		a. Centrisch belaste kolommen
		b. Excentrisch belaste kolommen
		c. Berekening tegen knik.
Afdeling IV Omweekend beton		

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part C2)

G.B.V. 1940	G.B.V. 1950	GBV 1962
Afdeeling IV Berekeningen	Afdeeling IV Berekeningen	Afdeling V Berekeningen
§27 Berekeningen	§27 Berekeningen	§36 Algemeen
§28 Grondslagen voor de berekeningen	§28 Grondslagen voor de berekeningen	Omschrijving Lengte van overspanning en opleggingen
a. Definities	a. Definities	Eigen gewicht
b. Lengte van overspanningen en opleggingen	b. Lengte van overspanningen en opleggingen	Belastingen
c. Eigengewicht	c. Eigengewicht	Stootcoëfficiënt
d. Belastingen	d. Belastingen	T-balken
e. Stootcoëfficiënt	e. Stootcoëfficiënt	§37 Statisch onbepaalde constructies
f. T-balken	f. T-balken	§38 Liggers van constante doorsnede met rechte as en gelijke veldlengte l_t
§29 Statisch onbepaalde constructies	§29 Statisch onbepaalde constructies	§39. Rechthoekige platen van constante dikte langs twee evenwijdige zijden ondersteund
§30 Momenten. Dwarskrachten. Steunpuntreacties	§30 Momenten. Dwarskrachten. Steunpuntreacties	Rechthoekige, aan 4 zijden ondersteunde platen van constante dikte, met
§31 Inwendige spanningen	§31 Inwendige spanningen	§40 gelijkmatig verdeelde belasting
a. Buigspanningen (trek- en drukspanningen)	a. Buigspanningen (trek- en drukspanningen)	§41 Rechthoekige, aan 4 zijden ondersteunde platen van constante dikte, waarvan $l_y/l_x \leq 2.5$ met
b. Spanningen door dwarskrachten (schuine trekspanningen)	b. Spanningen door dwarskrachten (schuine trekspanningen)	geconcentreerde belastingen
§32 Kolommen	c. Schuine trekspanningen in platen rond om geconcentreerde lasten	§42 Inwendige spanningen
a. Centrisch belaste kolommen	§32 Kolommen	§43 Kolommen
b. Excentrisch belaste kolommen	a. Centrisch belaste kolommen	
c. Knik	b. Excentrisch belaste kolommen	
	c. Knik	

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part D)

G.B.V. 1940	G.B.V. 1950	GBV 1962
Afdeeling V Toelaatbare spanningen	Afdeling V Toelaatbare spanningen	Afdeling V Toelaatbare spanningen, doorbuiging, scheurwijdte
§33 Toelaatbare spanningen, indien geen bouwcontrôle wordt uitgeoefend volgens Afd. VI	§33 Toelaatbare spanningen, indien geen bouwcontrôle wordt uitgeoefend volgens Afd. VI	§44 Toelaatbare spanningen §45 Doorbuiging §46 Scheurwijdte
A. Drukspanningen in het beton	A. Drukspanningen in het beton	Afdeling VII Breukmethode
B. Trekspanningen en drukspanningen in de wapening	B. Spanningen in de wapening	§47 Algemene berekening
C. Schuine trekspanning in het beton	C. Schuine trekspanning in het beton	§48 Benadering
§34 Toelaatbare spanningen, indien wel bouwcontrôle wordt uitgeoefend volgens Afd. VI	§34 Toelaatbare spanningen en daarmee samenhangende bijzondere voorwaarden, indien wel bouwcontrôle wordt uitgeoefend volgens Afd. VI	§49 Beperkingen
A. Drukspanningen in het beton	A. Drukspanningen in het beton	Afdeling VIII Proefbelasting
B. Trekspanningen en drukspanningen in de wapening	B. Spanningen in de wapening	§50 Proefbelasting van bouwwerken
C. Schuine trekspanning in het beton	C. Schuine trekspanning in het beton	§51 Beproeving op breuk van constructiedelen

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part E)

G.B.V. 1940	G.B.V. 1950	GBV 1962
Afdeeling VI Bouwcontrôle	Afdeeling VI Bouwcontrôle	
§35 Toezicht en uitvoering	§35 Toezicht en uitvoering	
§36 Materialen	§36 Materialen	
§37 Fijnheidsmodulus	a. Zand	
§38 Plasticiteit	b. Grind	
a. Zetproef	c. Zand-grindmengsel	
b. Vloeiproef	§37 Fijnheidsmodulus	
§39 Geschiktheidsprof, controlegroep en verhardingsproef	§38 Plasticiteit	
a. Geschiktheidsproef	a. Zetproef	
b. Contrôleproef	b. Schudproef	
c. Verhardingsproef	§39 Geschiktheidsprof, contrôleproef en verhardingsproef	
§40 Kubusvastheid	a. Geschiktheidsproef	
	b. Contrôleproef	
	c. Verhardingsproef	
	§40 Kubussterkte	
Afdeeling VII Afwijkingen	Afdeeling VII Afwijkingen	
§41 Afwijkingen	§41 Afwijkingen	
	Afdeling VIII Paddestoelvloeren met vierkante of rechthoekige velden	Afdeling IX Paddestoelvloeren
	§42 Uitvoering	§52 Omschrijving en definities
	§43 Definities. Notaties	§53 Aanvullende notaties
	§44 Omschrijving van paddestoelvloeren	§54 Kolomkoppen, kolomplaten en kolommen
	§45 Paddestoelvloeren opgevat als doorgaande raamwerken	§55 Vloerdikte en doorbuiging
	§46 Paddestoelvloeren berekend met moment coëfficiënten	§56 Berekening
	§47 Coëfficiënten voor de buigende momenten	§57 Raamwerken-methode
	§48 Stroken en maatgevende doorsneden	§58 Momentcoëfficiënten-methode
	§49 Vloerdikten en kolomplaten	§59 Momentcoëfficiënten-methode
	§50 Koppen en consoles	§60 Maatgevende doorsneden
	§51 Wapening	§61 Openingen
	§52 Openingen	§62 Aanvullende wapeningsvoorschriften
	§53 Schuine trekspanningen	
	§54 Nadere bepalingen	
	A. Schema's van wapeningen	
	B. Buigende momenten in de kolommen	

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part A1)
- English version -

G.B.V. 1912	G.B.V. 1918	G.B.V. 1930
General definitions	General definitions	Section I General definitions.
§1 Definitions	§1 -	§1 Referring to the code of §2 practice. §3 Drawings Design
Section I Materials	Section I Materials	Section II Materials
§2 Cement	§2 Portlandcement	§4 Cement
§3 Sand	§3 Sand	§5 Sand
§4 Gravel and crushed stone	§4 Gravel and crushed stone	§6 Gravel and crushed stone
§5 Concrete	§5 Concrete	§7 Water
§6 Iron	§6 Iron	§8 Composition of concrete §9 Iron

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part A2)
- English version -

G.B.V. 1940	G.B.V. 1950	GBV 1962
Section I General definitions	Section I General definitions	Section I General definitions
§1 Referring to the code of	§1 Referring to the code of	§1 Scope and validity
§2 practice.	§2 practice.	§2 Specification
§3 Drawings	§3 Drawings	§3 Design en inspection
Design	Design	§4 Drawing and calculation
		§5 Deviation from the code
Section II Materials	Section II Materials	Section II Materials
§4 Cement	§4 Cement	§6 Cement
§5 Sand	§5 Sand	§7 Sand
§6 Gravel and crushed stone	§6 Gravel and crushed stone	§8 Gravel and crushed stone
§7 Water	§7 Water	§9 Fineness modulus
§8 Composition of concrete	§8 Composition of concrete	§10 Water
§9 Staal (steel)	§9 Steel	§11 Additives
		§12 Quality classes of concrete
		§13 Composition of concrete
		§14 Cube strength
		§15 Tests of suitability, controle and setting
		§16 Plasticity of concrete specimens
		§17 Steel

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part B1)
- English version -

G.B.V. 1912	G.B.V. 1918	G.B.V. 1930
Section II Construction	Section II Construction	Section III Construction and design
§7 Personnel	§7 Personnel	§10 Personnel
§8 Support and formwork	§8 Support and formwork	§11 Storage of materials
§9 Placing of reinforcement	§9 Placing of reinforcement	§12 Formwork. Workplace.
§10 Completion of reinforcement	§10 Completion of reinforcement	§13 Placing of reinforcement. Concretedekking
§11 Workmanship of concrete	§11 Workmanship of concrete	§14 Mixing and workmanship of concrete
§12 Construction joints	§12 Construction joints	§15 Construction joints
§13 Covering and keeping moist	§13 Covering and keeping moist	§16 Covering and keeping moist. Putting into service
§14 Frosty weather	§14 Frosty weather	§17 Frosty weather
§15 Minimum reinforcement content, coupling, and distance between bars	§15 Removal of the formwork §16 Openings. Blocks. Lathes. §17 Minimum reinforcement content, coupling, distance between bars and concrete cover	§18 Removal of the formwork. Honeycombs
§16 Testing	§18 Testing	§19 Openings. Blocks. Lathes. etc.
		§20 Reinforcement of slabs
		§21 Reinforcement of beams
		§22 Reinforcement of columns
		§23 Hooks, bending and welding of reinforcement bars
		§24 Minimum slab thickness
		§25 Testing. Prefabricated construction elements

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part B2)
- English version -

G.B.V. 1940	G.B.V. 1950	GBV 1962
Section III Construction and design	Section III Construction and design	Section III Construction
§10 Personnel	§10 Personnel	§18 Personnel
§11 Storage of materials	§11 Storage of materials	§19 Storage of materials
§12 Formwork. Workplace.	§12 Formwork. Workplace.	§20 Formwork and workplace.
§13 Placing of reinforcement. Concretedekking	§13 Placing of reinforcement. Concretedekking	§21 Placing of reinforcement.
§14 Mixing and workmanship of concrete	§14 Mixing and workmanship of concrete	§22 Mixing and workmanship of concrete
§15 Construction joints	§15 Construction joints	§23 Construction joints
§16 Covering and keeping moist. Putting into service	§16 Covering and keeping moist. Putting into service	§24 Setting §25 Casting during low temperatures
§17 Frosty weather	§17 Frosty weather	§26 Removal of the formwork, Honeycombs
§18 Removal of the formwork Honeycombs	§18 Removal of the formwork. Honeycombs	§27 Openings. Blocks. Lathes. etc.
§19 Openings. Blocks. Lathes. etc.	§19 Openings. Blocks. Lathes. etc.	
§20 Reinforcement of slabs	§20 Reinforcement of slabs	Section IV Design
§21 Reinforcement of beams	§21 Reinforcement of beams	§28 Concrete cover
§22 Reinforcement of columns	§22 Reinforcement of columns	§29 Hooks and bending
§23 Hooks, bending and welding of reinforcement bars in construction elements under bending	§23 Hooks, bending and welding of reinforcement bars	§30 embedment length
§24 Minimum slab thickness	§24 Minimum slab thickness	§31 Welding General Electric welding Autogenous welding
§25 Testing	§25 Testing	§32 Slabs
§26 Prefabricated construction elements	§26 Prefabricated construction elements	§33 Walls §34 Beams §35 Columns Tied columns Confined columns Composite columns

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part C1)
- English version -

G.B.V. 1912	G.B.V. 1918	G.B.V. 1930
Section III Calculation	Section III Calculation	Section IV Calculation
§17 Definitions	§19 Definitions and determination of specific gravity	§26 Calculation.
§18 Empiric rules	§20 Calculation	§27 Principles for calculation
§19 Statically indeterminate construction elements	§21 Statically indeterminate structures.	a. Definitions
§20 Moment	§22 (Moment)	b. Span width and bearing length
§21 Tensile and compressive stress	§23 Tensile and compressive stress	c. Dead load
Shear stresses	§24 Allowed stresses in reinforcement and concrete	d. Belastingen
§22 Allowed stresses in reinforcement and concrete	§25 Calculation of columns.	e. T-beams
§23 Allowed stresses when considering test results	§26 Buckling resistance	§29 Statically indeterminate structures
§24 Buckling resistance	§27 Calculation of plain columns.	§30 Moments. Shear forces. Reaction at bearing points
§25 T-shaped beams	§28 Special constructions	§31 Internal stresses
	§29 Referring to the code of practice.	a. Bending stresses (tensile and compressive stresses)
		b. Stresses due to shear forces
		c. Allowable stresses
		§32 Calculation of columns
		a. Centric loaded columns
		b. Excentric loaded columns
		c. Calculation of buckling.
Section IV Confined concrete		

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part C2)
- English version -

G.B.V. 1940	G.B.V. 1950	GBV 1962
Section IV Calculation	Section IV Calculation	Section V Calculation
§27 Calculationen	§27 Calculationen	§36 General
§28 Principles for calculationen	§28 Principles for calculationen	Scope
a. Definitions	a. Definitions	Span width and bearing length
b. Span width and bearing length	b. Span width and bearing length	Dead load
c. Dead load	c. Dead load	Loads
d. Belastingen	d. Belastingen	Impact factor
e. Impact factor	e. Impact factor	T-beams
f. T-beams	f. T-beams	§37 Statically indeterminate structures
§29 Statically indeterminate structures	§29 Statically indeterminate structures	§38 Beams with a continuous section with a straight axis equal field length
§30 Moment. Shear forces. Reaction at bearing points	§30 Moment. Shear forces. Reaction at bearing points	§39. Rectangular slabs with a continuous thickness supported on parallel sides
§31 Internal stresses	§31 Internal stresses	§40 Rectangular slab, supported in 4 sides with a continuous thickness with equally distributed loads
a. Bending stresses (tensile and compressive stresses)	a. Bending stresses (tensile and compressive stresses)	§41 Rectangular slab, supported in 4 sides with a continuous thickness, with $l_y/l_x \leq 2.5$, with concentrated loads
b. Stresses due to shear forces	b. Stresses due to shear forces	§42 Internal stresses
§32 Columns	c. Shear stresses in slabs near concentrated stresses	§43 Columns
a. Centric loaded columns	Columns	
b. Eccentric loaded columns	§32 Centric loaded columns	
c. Buckling	a. Eccentric loaded columns	
	b. Buckling	
	c.	

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part D)
- English version -

G.B.V. 1940	G.B.V. 1950	GBV 1962
Section V Allowable stress	Section V Allowable stress	Section V Allowable stress, bending, crack width
§33 Allowable stress, when no inspection is carried out as according to Section VI	§33 Allowable stress, when no inspection is carried out as according to Section VI	§44 Allowable stress
A. Compressive strength in the concrete	A. Compressive strength in the concrete	§45 Bending
B. Tensile and compressive stresses in the	B. Stresses in the reinforcement	§46 Crack width
C. reinforcement	C. Shear forces in the concrete	Section VII Fracture mechanics
§34 Shear forces in the concrete	§34 Allowable stress and related special requirements when an inspection is carried out according to Section VI	§47 General calculation
Allowable stress, when no inspection is carried out as according to Section VI	A. Compressive strength in the concrete	§48 Approach
A. Compressive strength in the concrete	B. Stresses in de reinforcement	§49 Limitations
B. Tensile and compressive stresses in the reinforcement	C. Shear forces in the concrete	Section VIII Test load
C. Shear forces in the concrete		§50 Test load of structures
		§51 Fracture testing of construction elements

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Overview of different editions of the Gewapend Betonvoorschriften G.B.V. (part E)
- English version -

G.B.V. 1940	G.B.V. 1950	GBV 1962
Section VI Bouwcontrôle	Section VI Bouwcontrôle	
§35 Inspection and construction	§35 Inspection and construction	
§36 Materials	§36 Materials	
§37 Fineness modulus	a. Sand	
§38 Plasticity	b. Gravel	
a. Slump test	c. Sand-Gravelmengsel	
b. Flow table test	§37 fineness modulus	
§39 Test of suitability, control group, and setting test	§38 Plasticity	
a. Test of suitability of intended concrete	a. slump test	
b. Testing of used concrete	b. Flow table test	
c. Setting test	§39 Test of suitability, control group, and setting test	
§40 Cube strength	a. Test of suitability of intended concrete	
	b. Testing of used concrete	
	c. Setting test	
	§40 Cube strength	
Section VII Deviations	Section VII Deviations	
§41 Deviations	§41 Deviations	
	Section VIII	Section IX
	Mushroom floor slabs with squared or rectangular fields	Mushroom floors
	§42 Construction	§52 Description and definitions
	§43 Definitions. Comments	§53 Additional comments
	§44 Description of mushroom floors	§54 Column heads, column slabs and columns
	§45 Mushroom slabs as continuous frameworks	§55 Thickness of slabs and bending
	§46 Mushroom slabs calculated with moment coefficients	§56 Calculation
	§47 Coefficients for bending moment	§57 Framework-methode
	§48 Strips and determining sections	§58 Moment coefficient methode
	§49 Thickness of slabs of columns	§59 Moment coefficient
	§50 Column heads and consoles	§60 Determining sections
	§51 Reinforcement	§61 Voids
	§52 Voids	§62 Supplementary codes of reinforcement
	§53 Shear stresses	
	§54 Detailed definition	
	A. Reinforcement diagrams	
	B. Bending moments in columns	
	Bending of reinforcement bars	

Note: articles in bold indicate new additions to previous editions of the G.B.V.

Appendix D

Overview of the historic concrete mixtures described in Dutch textbooks.

Overview of the historic concrete mixtures described in Dutch textbooks.

Proportions cement: aggregates	Cement	Fine aggregate	Gravel	Crushed stone	$\frac{Kg\ Cement}{m^3\ concrete}$	Reference
1:15	1	5	10	-	130	Boon (1920)
					125	Scharroo (1910a, 1916)
1:12	1	4	8	-	158	Scharroo (1910a, 1916)
					145	Boon (1913, 1920); Scharroo (1921)
					160	Scharroo (1942b)
					149	Bergsma (1934)
1:10	1	4	6	-	165	Boon (1913, 1920)
					163	Scharroo (1921)
					176	Bergsma (1934); Boon (1931)
					180	Scharroo (1942b)
					215	Dwars (1923)
					180	Scharroo (1942b)
1:9	1	3	6	-	210	Scharroo (1910a, 1916)
					180	Boon (1913, 1920)
					210	Dwars (1923)
					190	Scharroo (1921)
					194	Bergsma (1934); Boon (1931)
					200	Scharroo (1942b)
	1	3	-	6	196	Scharroo (1942b)

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Proportions cement: aggregates	Cement	Fine aggregate	Gravel	Crushed stone	$\frac{\text{Kg Cement}}{\text{m}^3 \text{ concrete}}$	Reference
1:8	1	4	-	5	200	Scharroo (1942b)
	1	3	5	-	210	Boon (1913, 1920); Scharroo (1921)
					216	Bergsma (1934)
					225	Scharroo (1942b)
	1	3	-	5	222	Scharroo (1942b)
Zandbeton	1	4	-	4	220	Scharroo (1942b)
	1	8	-	-	n/a	Minister van Oorlog (1906)
	10	18			n/a	Minister van Oorlog (1906)
1:7,5	1	2,5	5	-	250	Boon (1908)
					225	Boon (1913, 1920); Scharroo (1921)
					228	van Dijk & Van der Baan (1952)
					240	Scharroo (1942b)
					229	van Dijk & Van der Baan (1952)
1:7	1	2,5	-	5	240	Scharroo (1942b)
						Boon (1908, 1913, 1920); Scharroo (1921)
					240	Boon (1931); Van der Schrier (1938, 1942, 1949)
					243	Bergsma (1934)
					242	van Dijk & Van der Baan (1952)
1:6,5	1	3	-	4	254	Scharroo (1942b)
	1	2,5	4	-	260	Boon (1913, 1920); Scharroo (1921)
						Bergsma (1934); Van der Schrier (1938, 1942, 1949); van Dijk & Van der Baan (1952)
					259	van Dijk & Van der Baan (1952)
					270	Scharroo (1942b)
1:6	1	2,5	-	4	270	Scharroo (1942b)
	1	2	4	-	300	
					318	Scharroo (1910a, 1916)
					315	Dwars (1923)
					280	Boon (1913, 1920); Scharroo (1921)
Melan mix						Bergsma (1934); Boon (1931); Van der Schrier (1938, 1942, 1949); van Dijk & Van der Baan (1952)
	1	2	4	-	n/a	van Rossum (1902)
	1	2	-	4	291	Scharroo (1942b)
	1	2,5	-	3,5	292	Scharroo (1942b)
	1	3	3	-	280	Boon (1908, 1913); Scharroo (1921)
						Bergsma (1934); Boon (1931); Van der Schrier (1938)
					277	van Dijk & Van der Baan (1952)
	1	3	-	3	292	Scharroo (1942b)

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Proportions cement: aggregates	Cement	Fine aggregate	Gravel	Crushed stone	$\frac{Kg \text{ Cement}}{m^3 \text{ concrete}}$	Reference
1:5,4 (Hen- nebique mix)	1	1,7	3,7	-	273	van Rossum (1902)
1:5	1	2	3	-	390	Boon (1908)
					335	Boon (1913, 1920); Scharroo (1921)
					350	Dwars (1923)
						Bergsma (1934); Boon (1931); Van der Schrier (1938, 1942, 1949)
					324	van Dijk & Van der Baan (1952)
					322	Scharroo (1942b)
	1	2	-	3	350	Scharroo (1942b)
					420	Dwars (1923)
	1	2,5	2,5	-	335	Boon (1913, 1920); Scharroo (1921)
					324	Bergsma (1934)
	1	2,5	-	2,5	350	Scharroo (1942b)
	3	5	10	-	380	Boon (1908)
1:4,5	1	2	2,5	-	400	Boon (1908)
					370	Boon (1913, 1920); Scharroo (1921)
					390	Dwars (1923)
					353	Boon (1931)
						Bergsma (1934); Van der Schrier (1942, 1949)
					352	van Dijk & Van der Baan (1952)
	1	1,5	3	-	450	Boon (1908)
					370	Boon (1913, 1920)
						Boon (1931); Van der Schrier (1938, 1942, 1949)
					353	van Dijk & Van der Baan (1952)
	1	2	2,5	-	352	
					360	Scharroo (1942b)
1:4	1	2	2	-	430	Boon (1908); Dwars (1923)
					420	Boon (1913, 1920); Scharroo (1921)
						Bergsma (1934); Boon (1931); Van der Schrier (1938, 1942, 1949)
					388	van Dijk & Van der Baan (1952)
					380	Scharroo (1942b)
	1	2	-	2	438	Scharroo (1942b)
	1	4	0	-	350	Boon (1908)
	1	1,5	2,5	-	420	Boon (1920); Scharroo (1921)
						Bergsma (1934); Boon (1931); Van der Schrier (1938, 1942, 1949)
					388	van Dijk & Van der Baan (1952)
					382	
1:3,5	1	1,5	2	-	480	Boon (1908); Dwars (1923)
					470	Boon (1913, 1920); Scharroo (1921)

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Proportions cement: aggregates	Cement	Fine aggregate	Gravel	Crushed stone	$\frac{\text{Kg Cement}}{\text{m}^3 \text{ concrete}}$	Reference
					431	Boon (1931)
						Boon (1931); Van der Schrier (1938, 1942, 1949)
					430	
					422	van Dijk & Van der Baan (1952)
					440	Scharroo (1942b)
1:3	1	1	2	-	580	Boon (1908)
					550	Boon (1913, 1920); Scharroo (1921)
	1	1,5	1,5	-	530	Boon (1908); Dwars (1923)
					550	Boon (1913, 1920); Scharroo (1921)
					490	Scharroo (1942b)
	1	3	0	-	450	Boon (1908)
Monier mix for vaults	1	3	0	-	n/a	van Rossum (1902)
1:2,5	1	1	1,5	-	630	Boon (1913, 1920)
					670	Scharroo (1921)
					610	Dwars (1923)
						Bergsma (1934); Boon (1931); Van der Schrier (1938, 1942, 1949)
					554	van Dijk & Van der Baan (1952)
					570	Scharroo (1942b)
1:2	1	1	1	-	840	Boon (1913); Scharroo (1921)
					740	Boon (1920)
					660	Scharroo (1942b)

End of table

Appendix E

Pigments used for historic concrete

Supplementary to Section 7.5 *Constituents to colour concrete*, more detailed information on the different pigments used to change the colour of historic concrete will be outlined in this appendix. The information presented is based on historic textbooks. The different background of the authors (engineers, chemists) and the type of reference (general concrete textbook, specific paint or chemistry books) has to be considered. It can be noticed that the terminologies used in the books were sometimes common trade names for pigments, historic terms, generic chemical terms or detailed chemical names. In addition, the period investigated overlaps with the transition from natural pigments to the development of synthetic pigments, influencing the naming and chemical understanding.

A direct classification of the pigments mentioned in historic (non-chemistry) references works is not always possible. Therefore, this appendix gives mainly an orientation of different pigments which could be encountered in historic concrete. Further material research would be necessary to identify the possible pigment used for a historic concrete. Some pigments formerly used for concrete are not used anymore, as they appeared not to be sufficiently durable. This has to be kept in mind as the present day colour might deviate from the original colour.

For detailed, general information on pigments see Buxbaum & Pfaff (2005); Parry & Coste (1902); van den Broeke (1919); Van der Kloes, Jacobs, Tjaden & Wentholt (1926); the application of concrete pigments are addressed in historic documents in varying degrees of detail (for example, Ast, 1907; Büsing & Schumann, 1905; Cimenteries et Briqueteries Réunies N.V. (C.B.R.), 1934; CUR report 36, 1966; Kind-Barkauskas, 2003; Lea & Desch, 1935; Onderdonk, 1928; Probst, 1919; Püttbach, 1987; Råde, 1968; Ramachandran, 1995; Roelofsen, 1950; Scharroo, 1942b; Van der Kloes, 1893; Von Szadkowski, 1969).

For historic concrete, the following colours were discussed: green, black, brown, yellow, blue, red, and white.

Green concrete was achieved by adding chromium oxide or iron oxide pig-

ments. Chromium oxide green (Dutch *chroomgroen*, *chromoxyde*, German *Chromoxidgrün*) was rather expensive. Green colour was also achieved by mixing different pigments: chromate green was a mixture of chrome yellow with Berlin blue (Van der Kloes et al., 1926), but according to the CUR report 36 (1966), chromate green should not be used. Iron oxide green (German *Eisenoxidgrün*) is a mixture “of iron oxide yellow with an organic blue pigment or a mixture of iron oxide yellow with iron oxide black [and] is not advised, as the organic pigments are not stable and the colour changes from green to yellow” (Püttbach, 1987). Green was also possible using natural minerals: malachite and azurite, later these were also artificially produced. Chemically, such green pigments were known as copper carbonate, obsolete terms are malachite, azurite, basic carbonate of copper, green vediter, green bice, or mountain green (Onderdonk, 1928; Parry & Coste, 1902). No longer available is the historically used ultramarine green (Büsing & Schumann, 1905; Buxbaum, 1998; Probst, 1919). Scheele’s green (CuHAsO_3 , arsenite of copper, cupric hydrogen arsenic, cupric arsenite; Dutch *Scheele’s groen*; German *Kalkgrün*, *Scheelesche grün*, *Erdgrün*, *grüne Asche*) was discussed for concrete, yet as it is toxic and fades easily, its use was not advised (Parry & Coste, 1902; Probst, 1919; van den Broeke, 1919). Copper phthalocyanine green (Dutch *phthalocyaninegroen*) was limited usable (Råde, 1968).

Black was commonly made with organic pigments. Lea & Desch (1935) considered black as the most difficult colour, as the best colour result could be achieved with carbon black, which however affected the strength; pigments based on iron oxide or manganese did not result in a good colour. Most commonly discussed was nevertheless carbon black (lamp black, ivory black, bone black; Dutch *koolasch*, *roet*, *beenzwart*; German *Lampenschwarz*, *Elfenbeinschwarz*). A limited use was advised, as the colour could fade due to a washing out of the pigments (Råde, 1968), and if used the the pigment content for carbon black should be limited to 1%, for lampblack to 3% (CUR report 36, 1966). Ground coke (German: *Zementschwarz*, *Kohleschwarz*, *Kohlenschwärze*) was mentioned in historic textbooks, and considered a cheap pigment; it is not entirely lightproof, and if the pigments are too large, they can cause a deterioration of the concrete (Ast, 1907; Büsing & Schumann, 1905; Probst, 1919). Inorganic iron oxides were considered better to achieve black concrete. Iron oxide black (Fe_3O_4 , Dutch: *ijzeroxydezwart*; German: *Eisenoxidschwarz*) was seen suitable and was discussed in the second half of the 20th century (CUR report 36, 1966; Kind-Barkauskas, 2003; Püttbach, 1987; Råde, 1968; Scharroo, 1942b; Von Szadkowski, 1969). Manganese dioxide (MnO_2 , Manganese black; cement black; Dutch: *bruinsteen*, *mineraalzwart*, *mangaanzwart*; German: *Manganschwarz*, *Braunstein*, *Mangandioxid*, *Mangansuperoxyd*, *Cementschwarz*) was considered usable and discussed already earlier (Ast, 1907; Büsing & Schumann, 1905; Probst, 1919; Råde, 1968; Roelofsen, 1950).

Brown concrete could be made by mixing iron oxide red with organic carbon black, but the colour was not durable as the carbon black could be washed out, making the concrete redder (Probst, 1919; Råde, 1968). More durable are brown inorganic iron pigments, and many historic terms exist for the different types of

brown. An iron oxide with a manganese dioxide (MnO_2) content of 5-20% was traditionally called umber (Roasted iron oxide; Dutch: *ijzeroxydebruin*; German: *Umbra*). Both natural and synthetic iron oxides are used (Ramachandran, 1995) and considered to have a good usability for concrete (Råde, 1968). When less than 1% manganese dioxide was added to the iron oxide, the resulting pigment was called Sienna or Tierra di Sienna (Dutch: *Italiaansche aarde*, *Terra de Sienna*, *mahagonibruin*, *grand Italiaansche lak*) (Parry & Coste, 1902; Van der Kloes et al., 1926).

Yellow concrete is made with inorganic pigments. When using iron oxide pigments, the pigment was called (yellow) ochre (Dutch: *ijzeroxidegeel*, *oker*, *geel ijzererts*; German: *Eisendioxidgelb*, *Ocker*, sometimes wrongly named *Zinkgelb*). Only a limited use of ochre was initially advised as it influenced the strength of the concrete (Probst, 1919), later no concerns were expressed (Råde, 1968). Chromate pigments could be based on lead, such as chrome yellow ($\text{Pb}(\text{CrS})\text{O}_4$, lead chromate, yellow chromate of lead; Dutch: *chromaat geel*; German: *Chromatgelb*). Lead oxide pigments seriously affect the setting and hardening of cement (Lea & Desch, 1935). Zinc chromate (ZnCrO_4 ; Dutch: *Zinkgeel*; German: *Zinkgelb*, sometimes wrongly named *Ultramarinegelb*), was an expensive pigment and rarely used for cement products (Probst, 1919). Naples yellow (Dutch: *Neapelgeel*; German: *Neapelgelb*) could have been made with a variety of pigments (Parry & Coste, 1902). It could be used for concrete, yet it was not resistant to sulphates (CUR report 36, 1966; Råde, 1968). Other suitable pigments to achieve yellow was nickel titanium yellow (Dutch: *nikkeltitaangeel*; German: *Nickeltitangelb*, *Lichtgelb*); cadmium yellow was not advised (Råde, 1968).

Blue pigments were heavily discussed, as not all were lightproof and some even were detrimental. Iron blue pigments, known as Paris blue, Berlin blue, Milori blue, or Prussian blue (Dutch: *Berlinsch blauw*, *Parijsch blauw*; German: *Berliner blau*, *Preussisch blau*, *Milori blau*, *Pariser blau*) should not be used for concrete (CUR report 36, 1966; Råde, 1968). Better was the use of cobalt aluminate (cobalt blue, oxide of cobalt; Dutch: *Kobaltblauw*, *smaltblauw*, *koningsblauw*, *Thénardsblauw*, *lichtblauw*; German: *Kobalt-Aluminium-Chromoxid*, *Kobaltblau*, *Thénardsblau*). An expensive blue pigment was the natural pigment blue ultramarine (Egyptian blue, Dutch: *Ultramarijn*, *ultramarine blauw*, *Egyptisch blauw*, *Vesturiaansch blauw*; German: *Ultramarineblau*, *blaues Ultramarine*), now it is synthetically made. Its suitability was controversially discussed; Probst (1919) considered it as the only cement colour which did not affect the strength of the concrete; Lea & Desch (1935) described that the colour would slowly fade as the pigments would combined with the free calcium hydroxide; they also did not advise the use of Prussian blue. Limited suitable was manganese blue (Dutch: *mangaan blauw*; German: *Manganblau*) (Råde, 1968). As organic pigment, phthalocyanine blue (Dutch: *phthalocyanineblauw*; German: *Kupferphthalocyanin*) could be used, but they were considered less light proof (Råde, 1968).

For **red** concrete, mainly iron oxide pigments were discussed. Many historic synonyms existed for red iron oxide pigments which were not always applied con-

sistently (e.g. caput mortuum (vitrioli), ochre: Spanish red, Persian red, Venetian red; Dutch: *Ijzeroxyderood*, *doodekop*, *caput mortuum (vitrioli)*, *ochres*, *Pruisisch*-, *Neuenberger*-, *Venetiaansch*-, *Persisch*-, *Antwerpsch*-, *Spaans en Parijsch rood*; German: *Eisenoxidrot*, *Oxydrot Englischrot*, *Caput mortuum*, *Eisenrot*, *Eisenoxid*). *Caput mortuum* was advised to colour cement (van den Broeke, 1919); venetian red faded when used for concrete (Taylor & Thompson, 1905). Warnings of high contents of sulphuric acid in iron red which could destroy the concrete were expressed (Büsing & Schumann, 1905). Cadmium red should neither be used for colouring concrete (CUR report 36, 1966; Råde, 1968).

White concrete is made by using a white cement (see Section 3.6.3 *White cement*), but adding titanium dioxide (TiO_2) can increase its brilliance (Püttbach, 1987). In the 1920s, titanium dioxide was too new on the market to judge its application (Van der Kloes et al., 1926). Other early available pigments, such as zinc sulphide (Lithopone; Dutch: *Litopoon*; German: *Lithopone*), could be mixed with iron pigments (Probst, 1919); zinc oxide should not be used (CUR report 36, 1966; Probst, 1919). As white cement was initially not easily available, it was suggested to modify the grey colour of Portland cement by adding lime (Van der Kloes, 1893), often in combination with white sand or finely ground marble (Büsing & Schumann, 1905; Taylor & Thompson, 1905).

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List of symbols and abbreviations

σ	stress, N/m ²
σ_s	yield strength, N/m ²
V_t	ultimate tensile strength, N/m ²
ACI	American Concrete Institute
CEMIJ	<i>Cement Industrie IJmuiden</i> - Cement Industry IJmuiden
CUR	<i>Commissie voor Uitvoering van Research; Civieltechnisch Centrum Uitvoering Research en Regelgeving</i>
Docomomo	DOcumentation and COnservation of buildings, sites and neigh- bourhoods of the MODern MOvement
ENCI	<i>Eerste Nederlandse Cement Industrie</i> - First Dutch Cement Industry
ICOMOS	International Council on Monuments and Sites
ICRI	International Concrete Repair Institute
IFS	<i>Institut für Steinkonservierung</i>
RDMZ	<i>Rijksdienst voor de Monumentenzorg</i>
UNESCO	United Nations Educational, Scientific and Cultural Organ- isation

List of Figures

1.1	The Dresselhuys pavilion (Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928, situation 2008). Details of the degraded concrete staircase.	3
1.2	Overview (Van Nelle factory, J.A. Brinkman and L.C. van der Vlugt, 1926-1931, situation 2006).	5
1.3	Schematic drawing of the relationship between heritage values, degradation and interventions.	6
1.4	Details of the remains of a former Roman Castellum in Utrecht. . .	7
1.5	Former Sanatorium Zonnestraat (Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928, situation 2008).	12
1.6	Former storehouse Mercurius (Wormerveer, M. J. Stam, 1919, situation 2006).	12
1.7	Former radio station Kootwijk (J. M. Luthmann, J. Emmen, 1921-22, situation 2006).	13
1.8	Fort Bezuiden Spaarndam, part of the Stelling van Amsterdam (Defense Line of Amsterdam) (1897-1901, situation 2006).	16
1.9	Pumping Station Rotterdam (J. G. van der Grinten, H. J. Heijdenrijk, 1968, situation 2006)	18
1.10	Thesis outline.	28
2.1	Overview Fortification Hellevoetsluis, built from 1880 onwards; situation 2012.	39
2.2	Fort Vijfhuizen, Stelling van Amsterdam, 1899, situation 2006. . .	39
2.3	Illustration of the Hennebique system.	41
2.4	Overview Philips Gloeilampenfabriek N. V. in Eindhoven (front part, 1909-1911, A. Beltman, in the back extension, "Lichttoren" 1920/21, Bureau TABROS; situation 2007).	43
2.5	Reinforced concrete water tower (Rijswijk, N. Biezeveld, 1911, situation 2009).	43
2.6	Factory building (Calvé factory, Delft, 1905, situation 2010). . . .	43
2.7	Cenacle Church, Heilig Land Stichting (J. Stuyt, J. Margry, J. G. Wiebenga, 1913-1915, situation 2011).	45

2.8	Overview Hofplein railway viaduct in Rotterdam (van Hemert, 1900-1908, situation 2009).	45
2.9	Bron system (housing Betondorp, Amsterdam, D. Greiner, 1923-1925. Situation 2008).	49
2.10	High-rise housing the “Wolkenkrabber” (Amsterdam, J. F. Staal, 1932, situation 2009).	49
2.11	Two examples of architectural use of concrete in the 1930s. a) School <i>Eerste Openluchtschool</i> , Amsterdam, J. Duiker, 1929-1932, situation 2007. b) Housing Rotterdam, Schepenstraat, 1937, W. Th. ten Bosch, situation 2010.	51
2.12	Bunker, Atlantic Wall in Hoek van Holland (1942, situation 2011).	51
2.13	Timeline for binders used for historic concrete.	56
2.14	Timeline for aggregates used for historic concrete.	57
2.15	Timeline for the mix design for historic concrete.	58
2.16	Timeline for the reinforcement used for historic concrete.	59
2.17	Timeline for surface finishes applied to historic concrete.	60
3.1	Legend from a historic construction drawing (Fort Vijfhuizen, 1897).	68
3.2	Dutch advertisement for Belgian Portland cement.	68
3.3	1930s advertisement showing a variety of available cements.	68
3.4	The Noorderlsuis in IJmuiden; experiments were carried out to identify a suitable binder for the brackish water (Rijkswaterstaat with J. A. Ringers, lock houses by J. Emmen, 1921-1929, situation 2012).	71
3.5	Advertisement of the Dutch Cement syndicate.	73
3.6	Advertisement for four Dutch cements.	73
3.7	19 th century Dutch advertisement for German Portland cement.	81
3.8	Advertisements for <i>groenstreep cement</i> . a) Cover of the 1930 edition of the beton-kalender. b) Advertisement from the Dutch cement syndicate.	84
3.9	Advertisement for the American white Portland cement “Wit Medusa”.	85
3.10	Advertisement for German Dyckerhoff Weiss.	85
3.11	Information brochure for white cement, Cimenteries et Briqueteries Réunies N.V.	85
3.12	Dutch advertisement for German Rhenish trass.	97
3.13	Experiments carried out by Tuffstein- und Basaltwerke A.G. to test the resistance of different cements.	98
3.14	Photomicrograph showing Portlandite (Fort Bezuiden Spaarndam, 1897-1901).	105
3.15	Photomicrograph indicating coarse ground Portland cement (Fort Bezuiden Spaarndam, 1897-1901).	105
3.16	Photomicrograph showing coarse C ₂ S (sample from the Betondorp, 1920s).	105

3.17	Photomicrograph showing blast furnace slag (Pumping station Parksluizen, Rotterdam; G. J. Van der Grinten, 1967), image by T.G. Nijland.	105
4.1	Illustrations addressing the possible sources of the contamination of aggregates.	111
4.2	Comparison of grading curves of different Dutch sands.	114
4.3	Example of a plain concrete building with an optimised use of coarse aggregates (Fort Bezuiden Spaarndam, part of the Stelling van Amsterdam, 1897-1901).	116
4.4	Two examples of ASR encountered in historic concrete dating from the 1930s, showing a typical ASR crack pattern. a) Lorentz sluice (Kornwerderzand 1932, situation 2009). b) Decorative concrete element (social housing, Rotterdam, 1935, M. J. Granpré Molière and P. Verhagen, situation 2010).	119
4.5	Early example of reinforced concrete made with gravel (circumambulation passageway, Pilgrimage church, Brielle, 1912, situation 2010 during repair).	119
4.6	Example of use of gravel for exposed concrete (Pumping station Parksluizen, Rotterdam, G. J. van der Grinten, 1967, situation 2008).	119
4.7	Gun turret of Fort Bezuiden Spaarndam, 1897-1901, situation 2006. a) Original construction drawing. b) The gun turret (situation 2006). c) Fractured surface of the gun turret. d) Photomicrograph of thin section.	122
4.8	Combined use of natural stone and concrete with crushed stone (housing Rotterdam, Walenburgerweg, architect and exact date unknown ca. 1933, situation 2011).	123
4.9	Plain concrete from the Nieuwe Hollands Waterlinie, ca. 1850 made with broken bricks and a trass-lime binder.	124
4.10	Example of plain concrete made with broken bricks (Fortification Hellevoetsluis; situation 2012).	124
4.11	Sample of a concrete made with breeze from the Betondorp. a) Overview. b) Photomicrograph of thin section. c) Photomicrograph of thin section.	126
4.12	Section of a <i>korrelbeton</i> made with pumice.	128
4.13	Housing made with poured <i>korrelbeton</i> using the Greve system (Scheveningen, W. Greve, 1920-1922, situation 2006).	128
4.14	Public library building built with <i>korrelbeton</i> (Betondorp, Amsterdam, D. Greiner, 1926-1928, situation 2008).	128
4.15	Soffit panels made with vermiculite concrete (Train station Enschede, H.G.J. Schelling, 1950, situation 2009).	128
4.16	Details of columns of the Hofplein railway viaduct, showing discoloured gravel (Rotterdam, A. C. C. G. van Hemert, 1900-1908, situation 2009).	130

4.17	Local deviation of maximum aggregate size (earth retaining walls of the unfinished Groot Museum Kröller - Müller, national park Hoge Veluwe, H. van de Velde, 1921-1922, situation 2008).	130
4.18	Popular illustration of the concept of continuous grading and gap grading.	132
4.19	Example of aggregate size distribution according to the Fuller curve.	133
4.20	Dutch reference to grading curves used in the German reinforced concrete standard.	134
4.21	Pictures of sieves to determine the size distribution of fine and coarse aggregates.	134
4.22	An early Dutch example dating from 1936 of gap-graded concrete made with blastfurnace slag cement (Sewage water reservoir, below the Jonas Daniel Meijer square, Amsterdam, picture 2008 by Timo G. Nijland).	136
5.1	Interior view of the main hall of Radio Kootwijk (J. Luthmann, J. Emmen, 1920-1923, situation 2006).	144
5.2	Illustration addressing the use of contaminated mixing water.	149
5.3	Water content in percentage (weight) in relationship with the compressive strength kg/cm^2 and classification of workability (Scharroo, 1949).	150
5.4	Water content in percentage (volume) in relationship with the compressive strength kg/cm^2 and classification of workability (Scharroo, 1949).	150
5.5	Different consistencies of fresh concrete (Scharroo, 1927b).	153
5.6	Example of corrosion induced by chlorides (<i>Dresselhuys pavilion</i> , part of <i>Sanatorium Zonnestraal</i> , Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928).	158
6.1	Example of a plain concrete vault (Fort near Vijfhuizen, 1899, situation 2006).	162
6.2	Schematic construction drawing of plain concrete vaults between iron I-section beams for floor constructions (Verhey, 1912).	162
6.3	Systematic drawings of the location of the reinforcement in a slab and a cantilever in relationship with the bending moment (Bergsma & Homan van der Heide, 1910b).	163
6.4	Section through floor slab at a negative bending moment above a beam, showing two reinforcement layers (Philips Lichttoren, building EC, Eindhoven, A. Beltman, 1909-11, situation 2007).	163
6.5	Example of a crack between two adjacent building elements in a plain concrete structure (Fort near Vijfhuizen, 1899, situation 2007).	166
6.6	Advertisement for Dutch reinforced concrete construction companies (Bergsma & Homan van der Heide, 1910a,b).	168

6.7	Advertisement for the <i>Hollandsche Maatschappij voor Gewapend Beton</i> (Boon, 1908).	168
6.8	Former headquarters of the <i>Koninklijke Rotterdamsche Betonijzermaatschappij v/h van Waning</i> (Rotterdam, J. I. van Waning, 1898, situation 2010)	168
6.9	Examples of reinforcement types (van Rossum, 1902).	175
6.10	Stress-strain diagram for steel (Bergsma, 1934).	179
6.11	Factory building designed according to the Monier system (<i>Calvé</i> factory, Delft, 1905, situation 2010)	183
6.12	Plain circular reinforcement bars (unfinished <i>Grote Museum, National Park Hoge Veluwe</i> , H. van de Velde, 1921-1922, situation 2008).	184
6.13	Plain circular reinforcement (Central Station Rotterdam, 1950-1957, S. van Ravesteyn, picture during demolition in 2008).	184
6.14	Examples of bar ends to increase the slip resistance (Boon, 1908).	185
6.15	Use of standard profiles (Fort near Vijfhuizen, 1899, situation 2006).	185
6.16	Example of the use of railway profiles in plain concrete military construction to support slab constructions.	186
6.17	Example of an unusual use of only rectangular reinforcement (bomb shelter near Fort Benoorden Spaarndam, 1916 - 1919, situation 2006, picture by T. G. Nijland).	188
6.18	Floor construction made with a combination of flat strips and round bars for reinforcement (Housing, The Hague, 1930s, exact year and architect unknown, situation 2009).	188
6.19	Example of the typical stirrups of the Hennebique system made with strips (former cotton warehouse Katoenveem Rotterdam, J. J. Kanters, 1920, situation 2009).	188
6.20	Stirrups made from strips in combination with plain reinforcing bars (emplacement of the Hofplein railway viaduct, Rotterdam, Van Hemert, 1904, situation 2009).	188
6.21	Oostelijke Singel bridge in Utrecht, now called Herenbrug made with rigid reinforcement using profiles (A. W. C. Dwars, 1906, situation 2011).	189
6.22	Example of rigid reinforcement made from L, T and I sections (Hofplein railway viaduct, Rotterdam, Van Hemert, 1900-1908).	190
6.23	Alpha steel reinforcement (Van der Schrier, 1953, p. 47).	191
6.24	Examples of different reinforcement bars mentioned in Dutch literature.	192
6.25	Dutch advertisement for different types of expanded metal (Bergsma & Homan van der Heide, 1910a).	193
6.26	Schematic drawings of the sea defence system De Muralt.	193
6.27	ISTEG bar.	195
6.28	<i>Getordeerd kruisstaal</i> (<i>Drillwulststaal</i>).	195
6.29	Drawing of view and section of a <i>Torwastaal</i> (Gantvoort, 1964).	196

6.30	Drawing of the view, section and symbol of a <i>Torstaal</i>	196
6.31	Ribbed reinforcement bars visible after demolition of a building. . .	196
6.32	Textural differences between historic and modern reinforcement (circumambulation passageway, Pilgrimage church, Brielle, 1912, situation 2010).	196
6.33	Drawings of the view and section of the most commonly used ribbed reinforcement bars used in the 1960s in the Netherlands (Gantvoort, 1964).	198
6.34	Comparison of a historic and present day welded mesh.	199
6.35	Connection of main and secondary reinforcement with annealed wires (Scharroo, 1916).	200
6.36	Picture showing the manual connecting of bars with wires (Bergsma & Homan van der Heide, 1910a, p. 164).	200
6.37	Examples of connections made with annealed wires.	202
6.38	Examples of wired connections.	203
6.39	Reinforcement of a balcony soffit with plain round bars as main reinforcement and a woven secondary reinforcement (former office building of the <i>Rotterdamsche Cementsteenfabriek van Waning & Co</i> , Rotterdam, J. I. van Waning, 1898, situation 2010).	203
6.40	Connection to extend bars with wires (left) and with coupling (right), (Boon, 1908, p. 78).	204
6.41	Example of a coupling of vertical reinforcement bars above a horizontal stirrups made with strips (emplacement of the Hofplein railway viaduct, Rotterdam, 1904, situation 2009).	204
6.42	Drawing explaining the concrete cover according to the G.B.V. 1962 (Anon., 1968, p. 71).	210
6.43	Illustrative drawing of misplacing the reinforcement (Scharroo, 1929).	211
6.44	Picture of an early concrete spacer (Boon, 1931, p. 126).	212
6.45	Example of the copper concrete spacer.	213
6.46	Overview drawing of testing beam (Van Hemert, 1901, appendix 3)	213
7.1	<i>Lichttoren</i> , Philips building ED, Eindhoven; Bureau TABROS1920/21, situation during intervention 2007.	217
7.2	Façade of a reinforced concrete building, combined use of artificial stone and <i>kunstzandsteenpleister</i> (artificial sandstone render, former hotel-restaurant “De Twee Steden”, The Hague, Joh. Mutters Jr, 1904-1906, situation 2010).	217
7.3	Prefabricated coloured concrete elements (Riveràhal of the Zoo Blijdorp, Rotterdam, van Ravesteyn, 1939-1941, situation 2011). . . .	217
7.4	Natural stone imitations (Faculty of Architecture, former Faculty of Chemistry, TU Delft, G. van Drecht, 1918-1923, situation 2011). . . .	217

7.5	Two early reinforced concrete buildings with façades made from traditional materials. a) Former bank building Rijkspostspaarbank, Amsterdam, D. E. C. Knuttel, 1899-1901, situation 2011. b) Town hall Rotterdam, H.J. Evers and A.J.Th. Kok, 1914-1920, situation 2009.	220
7.6	Natural stone imitation used in the former headquarters of the <i>Rotterdamsche Cementsteenfabriek Van Waning & Co</i> (Rotterdam, J. I. van Waning 1898, situation 2010).	220
7.7	Two examples of reinforced concrete structures rendered with <i>kunstzandsteenplaster</i> . a) St. Jobsveen Rotterdam, J.J. Kanters, 1912, situation 2010. b) Hofplein railway viaduct, Rotterdam, A. C. C. G. van Hemert, 1900-1908, situation 2009.	222
7.8	Exposed bush hammered concrete (former <i>Grand Hotel</i> , Amsterdam, G. J. Rutgers, G. van Arkel and H.J. Breman, 1925-1929, situation 2010).	223
7.9	Combination of brick, natural stone and exposed concrete.	225
7.10	Two examples of innovative application of concrete in the 1920s.	225
7.11	Example of use of decorative concrete instead of natural stone for sculptures due to material scarcity (Main entrance Zoo Blijdorp, Rotterdam, S. van Ravesteyn, sculptures L. Bolle, 1939-1941).	226
7.12	Overview of the Railway station Enschede (H.G.J. Schelling, 1950, situation 2009).	226
7.13	Two examples of exposed concrete buildings. a) Former <i>LTS Patrimonium</i> school (Amsterdam, J.B. Ingwersen, C. de Geus and C. v.d. Bom, 1952-1956, situation 2011). b) Auditorium TU Delft (architectural firm van de Broek en Bakema, 1959-66).	228
7.14	Reinforced concrete sculpture (Olympic stadium Amsterdam, F. Carasso, 1947, (situation 2007).	228
7.15	Decorative concrete elements (Grotius high school, The Hague, Sj. Schamhart, “drawings” by W.J. Rozendaal, 1949-1955, situation 2006).	230
7.16	Reliefs by B. Guntenaar at the entrance of the railway station Zutphen (H.G.J. Schelling, 1952, situation 2009).	230
7.17	Prefabricated concrete elements with a mosaic by L. van Roode (Holbeinhuis, Rotterdam, E.H.A. & H. M. Kraaijvanger, 1953, situation 2009).	230
7.18	On-site concrete wall with mosaic by H. op de Laak (former LTS Patrimonium school, Amsterdam, J.B. Ingwersen, C. de Geus and C. v.d. Bom, 1952-1956, situation 2011).	231
7.19	Sculpture (Sylvette, Rotterdam, P. Picasso, 1970, situation 2010)	231
7.20	Office building <i>Groothandelsgebouw</i> (Rotterdam, H. Maaskant & W. van Tijen, 1950).	232

7.21	Rendered plain concrete wall of a military building (Fort Bezuiden Spaarndam, part of the Defense Line of Amsterdam, 1897-1901, situation 2008) (a) Photograph. (b-d) Photomicrograph.	234
7.22	Soffit and head of a mushroom column (Van Nelle factory, J.A. Brinkman and L.C. van der Vlugt, 1926-1931, situation 2008). . .	235
7.23	Reinforced concrete rendered with a tooled <i>kunstzandsteen</i> (former warehouse St. Jobsveem, Rotterdam, J.J. Kanters, 1912, situation 2010).	236
7.24	Façade with artificial stone and <i>kunstzandsteenpleister</i> (artificial sandstone render, former hotel-restaurant “De Twee Steden”, The Hague, Joh. Mutters Jr, 1904-1906, situation 2010).	236
7.25	Example of an early reinforced concrete building with a tooled <i>kunstzandsteen</i> render and of colour changes of the render due to fire (Hofplein railway viaduct, Rotterdam, A. C. C. G. van Hemert, 1900-1908, situation 2010).	237
7.26	Stereo micrographic pictures from two differently coloured render samples of the emplacement of the Hofplein railway viaduct.	238
7.27	Examples of painted (plain) concrete military buildings (Fort near Hoofddorp, 1904, situation 2008).	239
7.28	Rear façade of the former fashion store Gerzon (A. Moen, Amsterdam, 1915, situation 2011).	241
7.29	Former radio station Kootwijk (J. M. Luthmann, J. Emmen, 1921-22, situation 2006).	242
7.30	Former industrial building HAKA (Rotterdam, H. F. Mertens, J. Koeman, 1931 - 1932). a) Picture taken during the bush hammering of the façade (Wattjes, 1934). b) Situation 2009.	242
7.31	Example of a bush hammered surface with chiselled margins (housing, 1930s, exact date and architect unknown, Rotterdam).	244
7.32	Example of <i>kathedraalslag</i> pattern, in combination with chiselled margins and point tooling on a reinforced concrete structure (Hofplein railway viaduct, Rotterdam, A. C. C. G. van Hemert, 1900-1908, situation 2010).	244
7.33	Concrete sculpture at the entrance of the Zoo Blijddorp, surface chiselled with <i>kathedraalslag</i> (Rotterdam, L. Boole; 1939-1941, situation 2011).	244
7.34	Example of horizontal, vertical and diagonal tooling with chiselled margins of prefabricated concrete elements (<i>Paleis van Justitie</i> , Arnhem, F. Sevenhuysen Jr., 1953-1963, situation 2010).	245
7.35	Prefabricated coloured concrete window sill; the texture has already partially eroded (housing, Rotterdam, exacts date and architect unknown, 1930s, situation 2010).	245

7.36	Details of the surface of the office building <i>De Nederlanden van 1845</i> , showing a render with a layer of small aggregates, instead of the original designed sand blasted surface, (The Hague, H.P. Berlage; 1921-27, extension 1954 by W. M. Dudok, partial reconstruction 1945-47, situation 2009).	247
7.37	Early example of exposed aggregates (" <i>Berlage Kiosk</i> ", The Hague, H. P. Berlage and J. G. Wattjes, 1925, situation 2011).	247
7.38	Example of the textural and colour effects of combining differently sandblasted concrete (Railway station Enschede, H.G.J. Schelling, 1950, situation 2009).	248
7.39	Column and window sill with sand blasted surface. The window sill was coloured with black carbon pigments (Railway station Enschede, H.G.J. Schelling, 1950, situation 2009).	248
7.40	Combination of sand blasted concrete columns and soffit with smooth surfaces at the sides of the elements (Railway station Arnhem, side entrance Sonsbeekzijde, H.G.J. Schelling, 1954, situation 2009). . .	249
7.41	Example of early application of exposed in-situ concrete (housing/commercial building, Utrecht corner Drift/Nobelstraat, 1920s, exact date and architect unknown, situation 2008).	249
7.42	Example of washed out prefabricated concrete element (Central station, The Hague, K. van der Gaast and J. Bak, 1968-1970, situation 2011).	250
7.43	Example of a polished concrete plinth (former <i>Twentsche Bank</i> , Rotterdam, A. van der Steur; W.A.C. Herman de Groot, B. Hooykaas, B. van Veen, A de Jong, 1946, situation 2010).	252
7.44	Prefabricated concrete elements filled with rubbed down concrete. As aggregates red and yellow broken bricks, and special Dutch blue coloured roof tiles (<i>gesmoord</i>), and white cement were used (Railway station Enschede, H.G.J. Schelling, 1950).	253
7.45	Former <i>Cafe la Reserve</i> in Amsterdam: the concrete elements were metallised in two different colours (J. van Schaik, 1918, situation 2011).	255
7.46	Advertisement of company <i>N.V. Algemeene Metallisatie en Betonbouw Compagnie</i>	256
7.47	Water tower in Zutphen (H. Sangster, 1927, situation 2009).	257
7.48	Three examples of timber formwork finish. a) Klokgebouw 'clock building', Strijp S, Eindhoven, A. de Broekert, 1928-1929, situation 2007. b) Unfinished Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008. c) Faculty Building for <i>Elektrotechniek, Wiskunde en Informatica</i> , TU Delft, J.P. van Bruggen, G. Drexhage, J.J. Sterkenburg & A. Bodon, 1959-1972, situation 2006.	260
7.49	Construction of RUBORA system, showing the supportive grid and building paper (Grin & van der Veen, 1950, p. 110).	262

7.50	Example of the combination of permanent formwork and timber formwork for exposed concrete (former school <i>Eerste Christelijke LTS Patrimonium</i> , Amsterdam, J.B. Ingwersen and C. de Geus, 1952-1956, situation 2011).	263
7.51	Example of smooth exposed concrete made on-site in combination with prefabricated concrete elements (<i>Groothandelsgebouw</i> , Rotterdam, H. Maaskant, 1950, situation 2008).	263
7.52	Drawings of the formwork of a mushroom floor construction column head (Grin & van der Veen, 1950, p. 53).	265
7.53	Geometric pattern based on a timber formwork of a mushroom floor (Van Nelle factory, J.A. Brinkman and L.C. van der Vlugt, 1926-1931, situation 2008).	265
7.54	Soffit with pattern consciously chosen by arranging individual timber boards (Train station Zutphen, H.G.J. Schelling, 1952, situation 2009).	265
7.55	Soffit above the entrance of the Auditorium TU Delft, as formwork combination of smooth panels and timber was used (architectural firm van de Broek & Bakema, 1959-66, situation 2006).	265
7.56	Soffit with different textures, sizes and orientation of formwork imprints (Provincial house Gelderland, Arnhem, 1950-1955, J.J.M. Vegter and H. Brouwer, situation 2010).	266
7.57	Example of the different patterns in prefabricated concrete elements made by inlays in the formwork (former tax office, Amsterdam, G. Friedhoff and M. Bolten, 1954-1958, situation 2011).	267
7.58	Drawing of a formwork with attached slats to imitate the joints of stonewall (Bergsma & Homan van der Heide, 1910a, p. 54).	268
7.59	Regularly placed openings for tie wires (Faculty of Architecture, Delft University of Technology, architectural firm van den Broek & Bakema, the building burnt down, May 13 th 2008).	268
7.60	Two examples of detail rich artificial stones. a) Former office building for Rotterdamsche Cementsteenfabriek van Waning & Co, Rotterdam, J. I. van Waning 1898, situation 2010. b) Former hotel-restaurant "De Twee Steden", The Hague, Joh. Mutters Jr, 1904-1906, situation 2010.	268
7.61	Entrance Radio Kootwijk, relief made in-situ by using gypsum formwork (J. M. Luthmann, J. Emmen, artist H. van den Eijnde, 1921-22, situation 2006).	269
7.62	Example of the use of a specially carved timber formwork for reliefs in concrete (G. Rietveld, Utrecht, Oudkerkhof, 1919, situation 2011).	270
7.63	Example of black and light coloured concrete elements (apartment buildings and garage, Slotterhof, Amsterdam, J.F. Berghoef 1958-1960, situation 2009).	272

7.64	Example of the use of white cement for a prefabricated window casing (Stationspostkantoor Arnhem, H. L. Engberts 1955-1961, situation 2010).	272
7.65	Example of red concrete elements (housing Slotershof, Amsterdam, J.F. Berghoef 1958-1960, situation 2009).	277
7.66	Example of beige and pink coloured prefabricated concrete elements (West wing of the “ <i>Rivièrahal</i> ” of the Zoo Blijdorp, S. van Ravesteyn, 1939-1941, situation 2011).	277
7.67	Chimney towers of two railway stations by H. G. J. Schelling. a) Railway station Enschede, 1950, situation 2009. b) Railway station Hengelo, 1952, situation 2009.	280
7.68	Façade of the railway station in Zutphen, prefabricated, sandblasted panels (H.G.J. Schelling, 1952, situation 2009).	280
7.69	Combination of <i>claustra</i> elements made with white Brunssum gravel and white cement (Railway station Enschede, H.G.J. Schelling, 1950, situation 2009).	281
7.70	Combination of different coloured concrete (Railway station Hengelo, H.G.J. Schelling, 1952, picture 2009).	281
7.71	Schematic drawing of pouring of a facing concrete.	283
7.72	Section through a prefabricated window sill with clearly visible facing layer and a reinforced backing concrete (1930s housing, The Hague).	283
7.73	Detail of a column base made from decorative concrete (Main entrance Blijdorp Zoo, Rotterdam, S. van Ravesteyn, 1939-1941, situation 2011).	283
7.74	Detail of a demolished window sill showing a beige coloured facing layer (housing, Rotterdam, 1930s, situation 2010).	285
7.75	Decorative concrete element, made with facing concrete (social housing, Rotterdam, M. J. Granpré Molière P. Verhagen, 1935, situation 2010).	285
7.76	Stair case made with prefabricated steps (Caballero factory, The Hague, 1953, F.A.W. van der Togt, situation 2009).	285
7.77	Advertisement for the decorative concrete brand artistone by <i>De Meteor</i> in the Journal Cement (1951), showing panels and claustra used by Schelling	287
7.78	Decorative concrete balustrades (Zoo Blijdorp, Rotterdam 1939-1941, situation 2010).	288
7.79	Example of small decorative concrete elements (housing, Rotterdam, architect and exact date unknown, 1930s, situation 2011). . .	288
7.80	Example of a sculpture in decorative concrete (former Giraffe compound, Zoo Blijdorp, Rotterdam, S. van Ravesteyn, 1939-1941, situation 2010).	289

7.81	Office building made with Artistone panels (Holbeinhuis H.A. & H. M. Kraaijvanger, Rotterdam, mosaic made by L. van Roode, 1951-1954, situation 2009).	289
7.82	Façade made with Artistone elements (Stationspostkantoor Rotterdam, E.H.A. & H.M. Kraaijvanger 1954-1959, situation 2009). . . .	290
8.1	Two exposed concrete surfaces with a smooth texture from the same period. a) Polished surface (Railway station Enschede, 1950, H.G.J. Schelling, situation 2009). b) Smooth surface texture made by using triplex formwork (Groothandelsgebouw, Rotterdam, H. Maaskant & W. van Tijen, 1950, situation 2008).	304
8.2	Two differently textured exposed concrete surfaces of the same building (Pumping station Parksluizen, Rotterdam; G. J. van der Grinten, 1967, situation 2007).	304
8.3	Example of a modified surface (office building <i>De Nederlanden van 1845</i> , The Hague, H.P. Berlage; 1921 -27, situation 2009).	305
8.4	Example of an intervention (railway station Zutphen, 1952, H.G.J. Schelling, situation 2009).	305
8.5	Example of aggregate types, sizes and grading reflecting the state of the art during construction time. a) Brikkenbeton with large aggregates and no middle fraction (military building, middle 19 th century). b) Crushed stone with no middle fraction (Fort Vijfhuizen, 1899, situation 2006). c) Use of gravel and different fractions but not well graded (St. Jobsveem, Rotterdam, J.J. Kanters, 1912, situation 2010). d) Use of gravel and gap-graded concrete (water cellar below J. Daniel Meyer plein, 1936, picture Timo G. Nijland). . . .	306
8.6	Two examples of buildings appreciated for the design yet with different approaches towards the original material. a) Calvé factory (<i>Moniergebouw</i>), Delft, 1905, situation 2010. b) Dresselhuys pavilion, Sanatorium Zonnestraal, Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928, situation 2008.	308
8.7	Example of the increasing impact of corrosion on an exposed concrete surface (Pumping station Parksluizen, Rotterdam; G. J. van der Grinten, 1967).	314
8.8	Biological growth on concrete surface, spalled concrete and corrosion (casement V, Defence line Kornwerderzand, 1933, situation 2009).	315
8.9	Loss of entire cross section of a reinforcement bar and parts of the concrete bulk (Dresselhuys pavilion, Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928, situation 2008).	315
8.10	Deposits caused by leaching and cracking (Fort near Hoofddorp, 1904, situation 2006).	315

8.11	Damage caused by impact of shells during the Second World War (kanonkazemat VI, 1932, Defence line Kornwerderzand, situation 2009).	315
8.12	Example of an early reinforced concrete structure based on a timber design and relating degradation due to the geometry of the design and quantity of reinforcement (circumambulation passageway of the Pilgrimage church in Brielle, H. Goossens (reconstruction), E.J. Margy, 1912 situation 2010).	317
8.13	Site plan Fort Bezuiden Spaarndam.	319
8.14	Overview gorge façade Fort Bezuiden Spaarndam (1897-1901, situation 2006).	320
8.15	Interior of Fort Bezuiden Spaarndam with visible wooden boards cast into the concrete (situation 2006).	320
8.16	Three different construction phases of the Hofplein railway viaduct (situation 2010).	323
8.17	Example of local damage of render and concrete, exposing the reinforcement (Hofplein railway viaduct 1900-1908, situation 2009).	325
8.18	Example of an arch without the original surface (Hofplein railway viaduct 1900-1908, situation 2012).	325
8.19	Location of the <i>brandgrens</i> (fire border) of the fire May, 1940 during the Second World War (Hofplein railway viaduct 1900-1908, situation 2012).	326
8.20	Example of different interventions and resulting surface finish (Hofplein railway viaduct 1900-1908, situation 2012).	326
8.21	Two examples of mismatching previous repairs, affecting the appearance of the surface (Hofplein railway viaduct 1900-1908).	327
8.22	Application of sprayed concrete in the vaults of the emplacement (Hofplein railway viaduct 1900-1908, situation 2009).	327
8.23	Overview of the earth retaining walls of the sculpture yard (Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008).	329
8.24	Overview of the walls of the terrace, which were initially intend to be earth retaining (Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008).	329
8.25	Overview of the site with the investigated retaining walls (Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008).	329
8.26	Examples of dispersed blocks of Maulbronn sandstone spread near the walls of the terrace (Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008).	330
8.27	Details of the construction to place the natural stone blocks (Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008).	330

8.28	Evidence of the sudden cease of the construction works (Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008).	331
8.29	Signs of merging with the landscape and local degradation (Groot Museum, Natural park Hoge Veluwe. H. van de Velde, 1922, situation 2008).	331
9.1	Example of the reconstruction of an entire housing project, (Kiefoek, Rotterdam, J.P.P. Oud, 1928-1930, demolition and reconstruction 1990-1995, situation 2009).	339
9.2	Reconstruction of façade panels (Housing <i>Jeruzalam Frankendaal</i> , Amsterdam, B. Merkelbach, Ch. J. F. Karsten, P. J. Elling 1947-1949, situation 2011).	339
9.3	Example of the impact of taking cores on the appearance. a) Fort Bezuiden Spaarndam, 1897 - 1901, situation 2008. b) Church of Our Lady, Dresden, plinth, situation 2011.	348
9.4	Schematic drawing, comparing of concrete removal for different treatments of corrosion induced by carbonation.	348
9.5	Demonstration of hydrodemolition on a historic concrete structure (Hofplein railway viaduct, Rotterdam, Van Hemert, 1900-1908, situation 2009).	350
9.6	Large scale concrete removal with hydrodemolition (circumambulation passageway of the Pilgrimage church in Brielle, H. Goossens (reconstruction), E.J. Margy, 1912, situation 2010).	350
9.7	Trial repair of three columns to test the workability (sprayed and poured polymer modified repair mortar) and quality of the surface finish (circumambulation passageway of the Pilgrimage church in Brielle, H. Goossens (reconstruction), E.J. Margy, 1912, situation 2010).	353
9.8	Column of an exposed concrete repaired with a polymer-based patch repair, showing discoloration due to ageing (Faculty of Architecture, TU Delft, architectural firm van de Broek & Bakema, 1960-1970, building burnt 13.05.2008, situation 2007).	353
9.9	Column foot made from decorative concrete with local repairs (Main entrance Zoo Blijdorp, Rotterdam, S. van Ravesteyn, 1939-1941).	354
9.10	Window opening made from prefabricated concrete elements, before (2009) and after (2010) trial repair (Stationspostkantoor Arnhem, H. Engberts, 1955-1961).	355
9.11	Repair of an exposed concrete surface made with blast furnace slag cement and gravel, originally with a wood grain structure (Pumping station Parksluizen, Rotterdam; G. J. van der Grinten, 1967, situation 2010).	356

9.12	Concrete made with diabase as aggregate and bush hammered surface margins (housing, 1930s, exact date and architect unknown, Rotterdam, situation 2011).	356
9.13	Column with exposed aggregate surface finish and standard grey patch repair (Train station Zutphen, H.G.J. Schelling, 1952, situation 2009).	356
9.14	Example of using sprayed concrete with a specially adapted repair concrete to reconstruct the roof of the conch of a church (Fatima church, Kassel, Germany, G. Böhm, 1957-1959, situation 2008). . .	359
9.15	Example of a large scale surface repair with sprayed concrete with possibilities to reconstruct the concrete ornaments (storehouse Mercurius, Wormerveer, M.J. Stam, 1919, restoration 1995-1997, situation 2006).	359
9.16	Detail of a corner of a concrete slab, the repair mortar has cracked in less than 6 years after repair and is visible due to soiling (Sanatorium Zonnestraal, Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928, restoration began in 2001, situation 2007).	361
9.17	Corner of an exposed concrete sculpture showing a cracked repair mortar with rust stains, indicating on-going corrosion (sculpture by C. Visser, TU Delft, 1966, situation 2006).	361
9.18	Examples of a crack injection with visible injection ports. a) Faculty of Civil Engineering, TU Delft, architectural firm van den Broek & Bakema, 1964-1975, situation 2006. b) Fort Bezuiden Spaarndam, 1897-1901, situation 2006.	363
9.19	Comparison of two concrete surfaces (former orphanage, Amsterdam, A. van Eyck, 1959-61, situation 2008).	366
9.20	Example of a grey painted, previously exposed, concrete surface (Olympic stadium, Amsterdam, J. Wils, 1928, situation 2008). . .	366
9.21	Example of the colour change caused by surface treatments (Train station Hengelo, H.G.J. Schelling, 1952, situation 2009).	366
9.22	Example of the visual impact of anti-graffiti coatings (Former tax office, Amsterdam, G. Friedhoff and M. Bolten, 1954-1958, situation 2011).	367
9.23	Section through a core showing a failed repair (concrete overlay) over a wide crack (plain concrete fort dating from 1895).	367
9.24	Example of a failure of a coating due to the presence of moisture on a plain concrete fort (Fort near Aalsmeer, 1904, repair 1996, situation 2006).	368
9.25	Schematic drawing of the setup of two different anode types and their impact on the historic concrete.	372
9.26	Example of external strengthening with an additional reinforced concrete layer (Dresselhuys pavilion, Hilversum, J. Duiker, B. Bijvoet and J. G. Wiebenga, 1928, situation 2008).	376

9.27 Example of FRP used to strengthen a glass brick floor (Vocational school (Ambachtsschool), Zwolle, A. Baart & L. Krook, 1934, situation 2011).	378
10.1 Example of the relationship of different states of the historic concrete.	392
10.2 Façade of the emplacement after being painted entirely white (Hofplein railway viaduct, situation 2012).	394
11.1 Schematic drawing of the four states of conservation.	405
11.2 Example of untreated cracks at the former construction joints caused by thermal stresses (arrow) (Fort Benoorden Spaarndam, 1897-1901, situation 2006).	409
11.3 Two different interventions of the active cracks caused by thermal movement (Fort Bezuiden Spaarndam, 1897-1901, situation 2006).	409
11.4 Example of honeycombs; plain concrete wall with crushed rock, cut through during a previous intervention (Fort near Hoofddorp, 1904, situation 2006).	410
11.5 Example of seepage through former construction joints and cracks caused by thermal stresses in the interior of the fort (Fort Bezuiden Spaarndam, 1897-1901, situation 2006).	410
11.6 Example of the visual impact of repaired cracks (Fort Bezuiden Spaarndam, 1897-1901, repair 1996).	411
11.7 Two examples of the reappearance of leaching after intervention. a) Fort near Vijfhuizen, 1899, conservation 2003-2005, situation 2006. b) Fort Bezuiden Spaarndam, 1897-1901, intervention ca. 1996, situation 2006.	412

List of Tables

1.1	Summary of the aims and intended readers/users of the thesis. . .	23
3.1	Comparison of proportions of blended cements.	67
3.2	Overview of the cement types allowed in the different editions of the G.B.V.	70
3.3	Overview of required fineness of the cement.	79
3.4	Overview of the composition of Portland cements discussed in Dutch literature.	82
3.5	Comparison of the composition of Portland cement and blast furnace slags.	90
3.6	Overview of the composition of <i>ijzerportlandcement</i> in Dutch literature.	93
3.7	Overview of the composition of hoogoven cement in Dutch literature.	94
3.8	Overview of the composition of supersulphated cement in Dutch literature.	95
3.9	Composition of German Trass.	97
3.10	Applied mixtures of trass and different binders	99
3.11	Overview of the composition of different mixtures of trass-Portland cement discussed in literature.	100
3.12	Overview of the composition of <i>erts cement</i> (Erz cement) discussed in literature.	102
3.13	Overview of the composition of aluminium cements discussed in literature.	103
4.1	Maximum sizes and grading of fine aggregates in different editions of the G.B.V.	113
4.2	Overview of coarse aggregates advised in historic Dutch concrete textbooks.	115
4.3	Maximum size for coarse aggregates in the different editions of the G.B.V.	131

5.1	Minimum cement content demanded in the different editions of the Gewapend Betonvoorschriften (G.B.V., Netherlands Code of Practice for Reinforced Concrete).	143
5.2	Overview of the main concrete mixes described in Dutch textbooks.	145
5.3	Concrete mixes used for some plain concrete forts of the Stelling van Amsterdam.	146
5.4	Overview of the water content of different concrete consistencies mentioned in historic Dutch concrete textbooks.	152
6.1	Overview of the irons and steel allowed in the different editions of the G.B.V.	173
6.2	Overview of types of iron and steel advised for reinforcement in Dutch literature.	174
6.3	Minimum concrete cover (mm) required in the different editions of the G.B.V.	208
6.4	Exposure classes according to NEN 5950:1995 VBT 1995 (NEN-EN 5950:1995).	209
6.5	Exposure classes related to the environmental conditions according to EN 1992-1-1: 2004 Eurocode 2, table 4.1	209
8.1	Overview of categories of heritage values officially used in the Netherlands.	301
8.2	Overview of possible material variables and aspects of the historic context to which heritage values can be correlated.	309
8.3	Overview of different degradation symptoms/alterations in relationship with the location.	313
9.1	Principles and Methods for protection and repair of concrete structures (NEN-EN 1504-9:2008).	337
11.1	Overview of possible aspects, which should be discussed when formulating the criteria for a dedicated conservation strategy.	403
D.1	Overview of the historic concrete mixtures described in Dutch textbooks.	471

Curriculum-vitae

Herdis Andrea Heinemann was born on May 24th, 1975 in Wolfratshausen, Germany. After completing the *Schiller Gymnasium* (grammar school) in Witten in 1994, she studied Architecture at the University of Dortmund, Germany. In 1999/2000 she participated in an academic exchange at the Delft University of Technology, Faculty of Architecture. In 2001, she graduated as *Diplom - Ingenieurin für Architektur und Städtebau*. Throughout her study, Herdis worked as part-time student assistant at several building societies. After completing her studies, Herdis worked as an architect at *Rapido-Haus GmbH Bauträgersgesellschaft*, Germany, until 2002. In 2001, she co-founded the architectural office *Hei.Di - Heinemann & Dickert - Planungsgemeinschaft für Architektur und Städtebau*. During this period, Herdis enjoyed the design, detailing and building site supervision of new housing projects and conversion of existing buildings. From 2006 to 2012 she conducted her PhD research at Delft University of Technology, chair of Building Conservation, Department RMIT, Faculty of Architecture. Currently, Herdis is working at the Materials & Environment group of the Faculty of Civil Engineering and Geoscience and coordinates the implementation of the new Ageing Centre for Materials and Structures, part of the TU Delft's Delft Centre for Materials.

When Herdis is not busy taking pictures of concrete and damaged buildings, and hunting antiquarian concrete books, she likes to play together with her husband Carlos Simão Ferreira and their son Fausto.

Propositions

1. One of the biggest threats towards historic concrete is the current lack of knowledge.
2. As long as the potential of pre-investigation and its benefits for conservation are not understood by practitioners, little progress will be made on the quality of conservation.
3. A problem of conservation is that we tend to use the wrong reference points: we evaluate an idealised past and ignore both the actual and the future state.
4. The wish to use checklists and universal solutions in conservation practice is a symptom for the lack of time, knowledge and resources, and misses the point that each conservation should be tailored.
5. Scharroo's complaint about concrete technology is still valid today: "*And yet is this so difficult, although it seems so simple.*" (Scharroo, P. W. (1938). *De vakopleiding van den betonarbeider. Voordracht gehouden voor de Betonvereniging op 16 December 1938*, p. 7.)
6. It is essential that material science, recognizing materials and their ageing behaviour are part of the education of architects and engineers.
7. A university library should not only offer the knowledge of the present and the future, but also cherish that of the past.
8. Also in concrete jungles, there are endangered species.
9. Part of a good heritage care is a neutral and competent central governmental agency.
10. Without understanding the *art of blending*, interventions of historic concrete buildings will not provoke an exploration of materials to achieve the often desired contrast between old and new.
(Based on the oration of Prof. Jo Coenen (2006), *De kunst van de versmelting/The art of blending*, TU Delft)

These propositions are regarded as opposable and defensible, and have been approved as such by the supervisor, Prof. ir. R. P. J. van Hees.

Stellingen

1. Een van de grootse bedreigingen voor historisch beton is het bestaande gebrek aan kennis.
2. Zolang de potentie van vooronderzoek en de voordelen daarvan voor de restauratie niet begrepen worden door uitvoerende partijen, zal de kwaliteit van restauraties weinig vooruitgaan.
3. Een probleem van de restauratie is dat we er naar neigen om de verkeerde referentiepunten te gebruiken: we evalueren een geïdealiseerd verleden en negeren zowel de bestaande als de toekomstige situatie.
4. De wens om in de restauratiepraktijk afvinklijstjes en universele oplossingen te gebruiken, is een symptoom van gebrek aan tijd, kennis en middelen, en gaat voorbij aan het feit dat elke restauratieopgave op maat gesneden zou moeten zijn.
5. Scharroo's klacht over betontechnologie geldt nog steeds voor de hedendaagse situatie: *"En toch is dit zoo moeilijk, al lijkt het op het oog nog zo eenvoudig!"*
(Scharroo, P. W. (1938). De vakopleiding van den betonarbeider. Voordracht gehouden voor de Betonvereniging op 16 December 1938, p.7)
6. Het is essentieel dat materiaalkunde, het herkennen van materialen en van hun verouderingsgedrag onderdeel zijn van de opleiding van architecten en ingenieurs.
7. Een universiteitsbibliotheek moet niet alleen de kennis van vandaag en morgen aanbieden, maar ook de kennis van het verleden koesteren.
8. Ook in een betonwoestijn zijn er bedreigde soorten.
9. Bij een goede monumentenzorg hoort een neutraal en vakbekwaam, centraal overheidsinstituut.
10. Zij die de *kunst der versmelting* niet verstaan, zullen niet geneigd zijn tot materiaalonderzoek aan historisch beton, dat juist nodig is om het gewenste contrast tussen oud en nieuw te bereiken.
(Gebaseerd op de oratie van Prof. Jo Coenen (2006). *De kunst van de versmelting/The art of blending*, TU Delft)

Deze stellingen worden oponeerbaar en verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotor, Prof. Ir. R.P.J. van Hees.