Spontaneous moss growth on concrete.

Master Thesis
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Spontaneous moss growth on concrete

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Preface

While finishing this master thesis "*Spontaneous moss growth on concrete*", I can reflect on a six month journey that has flown by. In these past couple of months I have learned a tremendous amount about the material concrete, different aspects of vegetation and moss growth, the construction industry, and not entirely unimportant, about myself. I was lucky to execute a research that combines my technical background from the master Structural Engineering with my interest in nature and willingness to contribute to a more sustainable world.

In this research process, I had the privilege to be mentored by a team of enthusiastic members, that were always there to help. The meetings we have had together supplied me with valuable insights and were not only productive, they were also a lot of fun.

First of all, I would like to thank the chair of my graduation committee, Henk Jonkers. With your help and guidance I was able to convert ideas into actual experiments. You were always interested in my work, and very supportive and enthusiastic about my ideas. Thereby you always had your door open, which I used eagerly. Secondly, I want to thank Maarten Swinkels from SGS Intron for his dedication to this research project. During your busy days there was always time for a meeting about the progress of this research, in which you gave your valuable input. With your help I was able to complete a lot of experiments in the SGS Intron laboratory. Next, I would like to thank Marc Ottelé for being my first supervisor. You supplied me, and sometimes even the other members of the committee, with a lot of contemporary concrete knowledge. You saw the gaps in the concrete knowledge, and pointed me in the right direction where needed. A special thanks to Gert van der Wegen, for providing me the opportunity to do my research at SGS Intron. Your knowledge and enthusiasm was very helpful. Last but certainly not least, I want to thank Tillmann Klein for being my second supervisor and for his help in transforming the knowledge obtained in this research into more concrete applications. You were able to get me out of my Structural Engineering mindset, and let me dream more about the possibilities that this spontaneous moss growth can give.

I would like to thank SGS Intron for the opportunity to conduct this research at their offices and laboratory. The information I gained from the skilled workers inside the laboratory was very valuable in designing my own research program, and without their help I would not have been able to execute this many experiments. Thank you for the support and interest in my project, and for providing me a great work space.

Finally, I want to thank my family, friends and of course Bob, for their endless support. Your enthusiasm and interest in this project has kept me motivated throughout this journey. A special thanks to my parents, Wouter and Irene Westhoff, for being so involved in this project, and taking pictures of every single object of moss concrete they could possibly find. This has definitely contributed to my own enthusiasm about this project. Thereby, I would like to say that I really enjoyed the time spend on this research, and I am very satisfied with the outcome.

Lonneke Westhoff
Rotterdam, March 2020

Executive summary

The most recent report of the United Nations illustrates that the world population will keep on increasing. With an overpopulated earth, green spaces are becoming more scarce. Especially in urban areas nature is sacrificed to keep up with the growing needs of society. The number of square meters of green space per capita is actually an indicator of the sustainability of a city, since green areas in cities can mitigate the city heat stress, improve aesthetics, increase the biodiversity, and capture particulate matter from the air.

A possible solution to have more green area in urban regions can be to have more green surfaces on buildings and structures, like green facades and green roofs. To realize this in an efficient, low maintenance, and cheap way, concrete could be designed to stimulate the growth of mosses. Spontaneous abundant moss growth on young concrete structures can actually already be observed in the build environment, however this is often unintentional and unwanted, and is seen as degradation of the concrete. A better understanding of why spontaneous moss growth occurs on some constructions while it does not on others can help to intentionally design green concrete structures, and eliminate unwanted spontaneous moss growth on concrete. Therefore the following research questions have been answered:

1. What are the most influencing material properties of concrete that determine the presence or absence of abundant spontaneous moss growth on current relative young concrete constructions, and how can these factors be influenced to either stimulate or inhibit moss growth?

2. What are the most important environmental performances of concrete with abundant moss growth, and can these environmental performances be quantified to gain more insight in the necessity of moss concrete in cities?

The main focus of this thesis was to answer the first research question. The second research question will give an insight in the positive benefits of moss concrete, and will show the construction industry its potential.

Answering research question 1
It has been found in this research that the curing conditions and the cement type being used are two major influencing factors that can contribute to the presence or absence of abundant moss growth on current relative young concrete constructions. A hospitable concrete surface is needed to support the growth of a biofilm, that can subsequently develop in moss. This hospitable concrete surface is provided by the concrete microstructure, a lowered pH, and a sufficient surface roughness.

In previous literature it has been found that the porosity and permeability of the cover zone of concrete plays a dominant role in predicting whether moss growth will occur. A positive relation has been found between a porous and permeable cover zone and moss growth. The porous and permeable cover zone will enable a high level of water absorption and retention, thereby creating an optimum environment for micro-organisms and vegetation to settle on, due to the provision of moisture for a long period after it has been raining. In this research experiments have been executed to analyse what could have caused this porous and permeable coverzone of concrete. A cause that can be found and is likely to attribute to this highly porous and permeable cover zone is the insufficient curing after casting of concrete, especially of concrete mixes with a low-clinker content. Research has found that the curing conditions have a major influence on the durability parameters, such as the porosity and permeability of concrete. It seems that during standard testing, which is after 28 days under water- or fog room curing in the laboratory, a low-clinker content concrete shows no signs of an imperfect cover zone, and actually performs sufficient when the strength and durability performance is considered. However, in practice the performance often fails to meet the potential of these concretes, especially the durability turns out to be much worse than what would have been expected based on the laboratory testing. Therefore, the following hypothesis is formed and tested: *A low-clinker content concrete (CEM III/B based) is more vulnerable for insufficient curing (air curing or paraffin curing) than concrete with a high-clinker content (CEM I), leading to a relatively more porous and permeable concrete cover zone.*

The high alkalinity of concrete ensures the durability and makes the coverzone an unattractive environment for micro-organisms to settle on. The buffer capacity towards alkalinity of a certain concrete mix can be explained as the ability to neutralize incoming acid without compromising on the alkalinity of the pore solution. In concrete with a low buffer capacity towards alkalinity the pH will decrease at the surface, providing an hospitable environment for micro-organisms. An effect of a low buffering capacity is that there is an increased risk of carbonation. Carbonation will lead to a more porous and permeable concrete for low-clinker content concrete, while it will ensure a denser microstructure for high-clinker content concrete. To test this effect a second hypothesis has been formed: *A low-clinker content concrete (CEM III/B based) will have a lower buffering capacity towards alkalinity than concrete with a higher clinker content (CEM I).*

To test both hypothesises mortar specimens were produced with three types of binder, that differ in clinker content. The specimens have been cured in three different ways, namely air curing, curing with a curing compound, and curing in water. To test the porosity and permeability of the samples a water absorption and drying test, Mercury Intrusion Porosimetry, an epoxy impregnation and a carbonation test have been conducted. The buffer capacity towards alkalinity has been tested with an buffer capacity test, that involves a titration set up.

From the results both hypothesises can be confirmed. A low-clinker content concrete is definitely more vulnerable for insufficient curing than concrete with a high-clinker content. The effect of air curing instead of water curing of a low-clinker content concrete leads to an increase of almost 99 % in water absorption, while for a high-clinker content concrete this increase in water absorption is only 29 %. The degree of water absorption is related to the porosity and permeability of concrete. The influence of the curing compound was different than what was expected. The samples cured with a curing compound have failed to hydrate better than air cured samples. The results from the carbonation test, epoxy impregnation and visual inspection confirm the results of the absorption test. From the performed experiments it can be concluded that a low-clinker content mix has a lower buffer capacity towards alkalinity than a high-clinker concrete mix.

To obtain concrete that is bioreceptive and will enable mosses to grow on its surface, a low-clinker content concrete must be used that is insufficiently cured. This will cause a porous and permeable outer layer of the concrete, that has been related to moss growth on concrete. Due to the low buffering capacity towards alkalinity, the pH at the cover zone of the concrete will be lower, thereby making the surface more attractive for micro-organisms to settle on. Another effect of insufficient curing is an increase in carbonation, which also leads to a more porous and permeable cover zone for low-clinker concrete.

To prevent moss growth on concrete, a dense microstructure and a high pH at the outer layer of the concrete must be created. This can be obtained by using a high-clinker content concrete. From this research it can be concluded that a high-clinker mix is relatively not very vulnerable for the curing conditions. A high-clinker content concrete will provide a dense microstructure and high buffer capacity towards alkalinity, even though it has been cured insufficiently.

Answering research question 2

The environmental performances of concrete with abundant moss growth on it have been investigated in this research. The air filtering capacity of mosses will lead to an improvement of the respiratory system, by absorbing fine particles of 10 μm and smaller that would otherwise be accumulated in the alveoli of the lungs. A lowering of 23% of asthma and COPD patients have been found amongst citizens that are surrounded by green. The acoustic properties of mosses contribute to a lowering of the community noise. An estimate of noise reduction when green roofs are being used is typically 3 dB, which is equivalent to half of the cars on the road, or half of the driving speed. The water retention capacity of mosses contribute to the cooling of buildings during summer, and provides insulating properties. An elevated amount of green space will lead to an improvement in mental and physical health. A decrease in anxiety disorder has been found of 31 % when exposed to 90 % of green space instead of only 10 %. Due to the water absorption capacity of mosses, urban flooding can be mitigated or even prevented. Thereby, the biodiversity will be increased if more green is applied in urban areas. The water absorption capacity and the annual CO_2 fixation have been quantified with experiments.

Two moss species have been tested in this research, namely the *Tortula Muralis* which is a pioneer moss and grows in cushions on concrete, and the *Hypnum Cupressiforme* which forms a moss mat on the concrete, and is often found after several years of moss growth. The moisture absorption of the moss specie *Tortula Muralis* is six times its dry weight and that of the moss specie *Hypnum Cupressiforme* is twelve times its dry weight. The moss *Hypnum Cupressiforme* has a fixing rate of 0,22 kg of CO_2 per year per m^2, and the moss *Tortula Muralis* fixates 0,50 kg of CO_2 per year per m^2.

The potential annual CO_2 fixation on country, city and building level is calculated. This potential annual CO_2 fixation as percentage of the total annual CO_2 emission on country, city and building level is between 0,2-1,2%.

This combined with the air filtering capacity, improved mental and physical health, noise reduction, mitigation of urban flooding and increased biodiversity can lead to an overall very positive impact.

The author draws several conclusions from literature, the conducted experiments and the case study. Firstly, moss concrete has several very important qualities that will contribute to more sustainable cities and mitigate climate change. The air filtering capacity, increase in biodiversity, cancelling of the surrounding noise, water retention capacity, and improvement in mental and physical health are all positive effects that occur when moss concrete is applied. Secondly, applying moss concrete in cities contributes to a lowering of the Urban Heat Island effect, due to the transpiration of the leaves and an increase in the albedo. Using moss concrete will improve the living environment of city inhabitants and multiple animal species. Finally, people in the Netherlands emit an enormous quantity of CO_2 annually. By lowering the CO_2 emissions, moss concrete will get a more prominent role in lowering the annual CO_2 emission in the Netherlands.

The overall conclusion of this research is that the implementation of moss concrete will lead to positive effects on physical, mental and environmental levels. Moss concrete enables humanity to contribute to restoring the negative consequences of our parasitic behaviour, and allows us to thrive in a more mutualistic relationship with planet earth.

Contents

Abbreviations

A - Al_2O_3 - Alumina

C - CaO - Calciumoxide - Lime

C_2S - $2CaO{\cdot}SiO_2$ - Dicalcium silicate

C_3A - $3CaO{\cdot}Al_2O_3$ - Tricalcium aluminates

C_3S - $3CaO{\cdot}SiO_2$ - Tricalcium silicate

C_4AF - $4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$ - Calcium ferroaluminate

$CaCO_3^{2+}$ - $CaCO_3^{2+}$ - Calcium carbonate

$\underline{C}$ - CO_2 - Carbon dioxide

CH - $Ca(OH)2$ - Calcium hydroxide or Portlandite

CSH - $3CaO2SiO_2H_2O$ - Calcium silicate hydrate

$C\underline{S}H_2$ - $CaSO_4{\cdot}2H_2O$ - Gypsum

$C_6A\underline{S}_3H_{32}$ - $6CaOAl_2O_33SO_3{\cdot}32H_2O$ - Ettringite

F - Fe_2O_3 - Ferric Oxide

H - H_2O - Water

M - MgO - Magnesiumoxide - Magnesia

S - SiO_2 - Silicium dioxide - Silica

$\underline{S}$ - SO_3 - Sulfur trioxide

Nomenclature

Å - 10^{-10} m - ångström

nm - 10^{-9} m - nanometer

μm - 10^{-6} m - micrometer

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Chapter 1

Introduction

The most recent report of the United Nations illustrates that the world population will keep on increasing, and is expected to grow from 7.7 billion people that live on the earth today to 9.7 billion inhabitants on planet earth in 2050 [30]. 10 years ago the expectation for the world population in 2050 was 9.2 billion people [31], showing that the expected population growth is advancing more rapid than expected. With an overpopulated earth green spaces are becoming more scarce, especially in urban areas nature is sacrificed to keep up with the growing needs of society [32]. This leads to multiple problems, particularly because it is expected that 80% of the population of world countries, with exceptions of some Asian and African countries, will live in cities by 2050 [33] [21]. The World Health Organization has made a list of indicators that contribute to the sustainability of a city, to reflect on the progress of more sustainable cities. One of these indicators is "the number of square meters of green space per capita", concentrating on the amount of green area that people have access to [33]. There are multiple reasons why the amount green space per individual is considered, green areas in cities can improve aesthetics, mitigate the city heat stress, increase biodiversity, and capture particulate matter from the air [32] [34] [35]. The WHO recommends a minimum availability of 9 m^2 of green area per individual, with an ideal value of 50 m^2 of green area per individual [32]. Researchers that have studied the development of green area in European cities found that several European cities fail to meet this minimum available green space per inhabitant recommended by the WHO [36].

A possible solution to have more green in urban regions can be to have more green surfaces on buildings and structures, like green facades and green roofs. To realize this in an efficient, low maintenance, and cheap way concrete could be designed to stimulate the growth of mosses [21] [37]. Spontaneous abundant moss growth on young concrete structures can actually already be observed in the build environment, however this is often unintentional and unwanted, and is seen as the degradation of the concrete [29]. A better understanding of why spontaneous moss growth occurs on some constructions while it does not on others can help to intentionally design green concrete structures, and eliminate unwanted spontaneous moss growth on concrete.

1.1 Research questions

The objective of this research is to gain a better understanding of why spontaneous moss growth occurs on some constructions while it does not on others. This will help to intentionally design green concrete structures, and eliminate unwanted spontaneous moss growth on concrete. The research questions that are formed to meet this objective are the following:

1. ***What are the most influencing material properties of concrete that determine the presence or absence of abundant spontaneous moss growth on current relative young concrete constructions, and how can these factors be influenced to either stimulate or inhibit moss growth?***
2. ***What are the most important environmental performances of concrete with abundant moss growth, and can these environmental performances be quantified to gain more insight in the necessity of moss concrete in cities?***

The weight of the research questions are not equivalent, the main focus of this thesis will be to answer the first research question with experiments. However, the second research question will give an insight in the positive benefits of moss growth on concrete, and will show the construction industry it's potential

1.2 Report outline

Part	Description	Chapter	Content
		Chapter 1	Introduction
Part I	Literature study	Chapter 2	City problems and solutions
		Chapter 3	Material properties of concrete
		Chapter 4	Moss growth on concrete
Part II	Experimental program and results	Chapter 5	Hypothesis formation
		Chapter 6	The experimental program explained
		Chapter 7	Results of the experiments
		Chapter 8	Discussion of the results
Part III	Case study	Chapter 9	Current moss concrete cases
		Chapter 10	Future potential of moss concrete
Part IV	Final part	Chapter 11	Conclusion
		Chapter 12	Recommendations

Table 1.1: Outline of this thesis

In Chapter 1 *Introduction* the subject of this research is introduced, and the research questions to be answered in this thesis are given. The outline for the report is shown.

Chapter 2 *Sustainable cities* is the first part of the literature study. The problems that cities are facing nowadays have been described, and a solution is proposed.

In Chapter 3 *Concrete* the literature study continues. The components, hydration processes, curing effects and properties of concrete are elaborated.

Chapter 4 *Moss concrete* is the last part of the literature study and focuses moss concrete. The potential benefits are given, and the growing process and influencing factors are explained.

Chapter 5 *Hypothesis formation* marks the beginning of the experimental program. In this chapter the knowledge obtained from the literature study is used to form hypothesises, that will be tested in this research.

In Chapter 6 *Experiments* the experiments chosen to test the hypothesises are explained, and the method and expected outcome is given.

The results of the experiments that are conducted are given in Chapter 7 *Results*.

Chapter 8 *Discussion* discussed the results of the experiments. Both hypothesises are answered at the end of this chapter.

The case study starts in Chapter 9 *Current situation*, that shows 11 case studies of moss covered concrete.

In Chapter 10 *Future potential* the case study continues, future scenarios that involve abundant moss concrete are presented.

In Chapter 11 *Conclusion* the conclusion of this research is given and both research questions are answered.

The final chapter of this research, Chapter 12 *Recommendations*, gives recommendations on this research, and provides future research topics.

Part I

Literature study

Chapter 2

Sustainable cities

At the moment cities have multiple environmental problems that threaten the well-being of millions living in urban areas [32]. The population is expected to grow to 9.7 billion people in 2050 of which 80% will be city dwellers, excluding some African and Asian countries. Therefore designing cities to be sustainable and livable is high on the agenda. This chapter contains some of the problems that cities are facing nowadays, and provides some of the solutions that can be found in literature. A future city design has been explored, and a solution strategy has been proposed that is further investigated in this thesis.

2.1 City problems

Due to expansion and densification of urban areas there is more pollution, an increased consumption of energy and resources, and an abundance of dumping grounds for different kinds of waste [38] [39]. Moreover this urban sprawl has led to the loss of green space and biodiversity in cities [40], and to the conversion of natural area and agricultural land into urbanized land [41]. Cities with little green space are vulnerable for several harmful effects, such as the urban heat island effect [42], and often lack ecosystem services [40]. The overall effect will lead to negative effects on food security and cause species extinction due to habitat loss and fragmentation [43]. These problems will become harder to ignore in the future, since it is predicted that our population will keep on increasing, and 80% of our overpopulated earth will be living in cities [30] [33]. To counteract against these issues, sustainable urban development should be high on the agenda. Proper city design could help to mitigate climate change, lower energy consumption, protect the biodiversity and provide a safe and healthy environment for its inhabitants [41]. To enable the development of livable and sustainable cities, a deeper understanding must be created of the problems that cities are facing nowadays. In this research the Urban Heat Island effect and the loss of ecosystem services in cities have been investigated.

2.1.1 The Urban Heat Island effect

Due to the loss of green space, and the conversion of natural land into urbanized land, the surface of a city changes [41]. What once were permeable and moist surfaces have become buildings and roads that are impermeable and dry. This leads to multiple environmental problems, like the storing and re-radiation of huge amounts of solar radiation and the reduction of air flow [44]. Urban areas become overpopulated, leading to increased heat generation by cars, air conditioners, power plants and other anthropogenic heat sources. This leads to a phenomenon that is called the Urban Heat Island effect, meaning that the temperature inside a city is higher than its rural surroundings, throughout the day and at night. Four hours after sunset the Urban Heat Island is supposed to be the strongest according to Unger et al. (2004) [45]. Research has shown that on cloudless days the temperature inside the Urban Heat Island can be 4.0 to 6.9 °C higher than its surroundings, during every season [46].

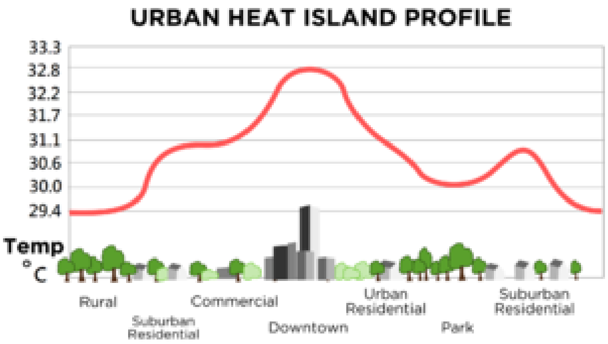


Figure 2.1: The urban heat island [1]

The Urban Heat Island effect deteriorates the living environment of city inhabitants and multiple animal species, increases the energy consumption due to more air conditioning use, and leads to elevated mortality rates [47]. The high temperature in the summer of 2003 was attributed to the death of 35.000 people in Europe [48]. Studies executed in the Netherlands between 1979 and 1997 shows that the mortality rate increased significantly during heat waves in cities, especially for inhabitants older than 65 years [49]. The ambient temperature increase was also studied, showing that the total mortality went up with 2.72% when the optimum temperature increased with a degree [48]. Measures that mitigate the Urban Heat Island effect are beneficial to multiple other areas, such as the lowering of energy costs, improving air quality and a decline in health risks. Research found that by mitigating the Urban Heat Island Effect in Houston, it was possible to save $82 million USD by a reduction of 730 MW peak power, and an decrease of the carbon emission [50].

The Urban Heat Island effect is influenced by multiple variables, which can be found in figure 2.2 [44]. Some of the variables are not directly controllable, like the weather. Other variables can be directly influenced to mitigate the Urban Heat Island. The focus in this thesis will be on the green area and building materials, both variables that can directly influence the Urban Heat Island effect.

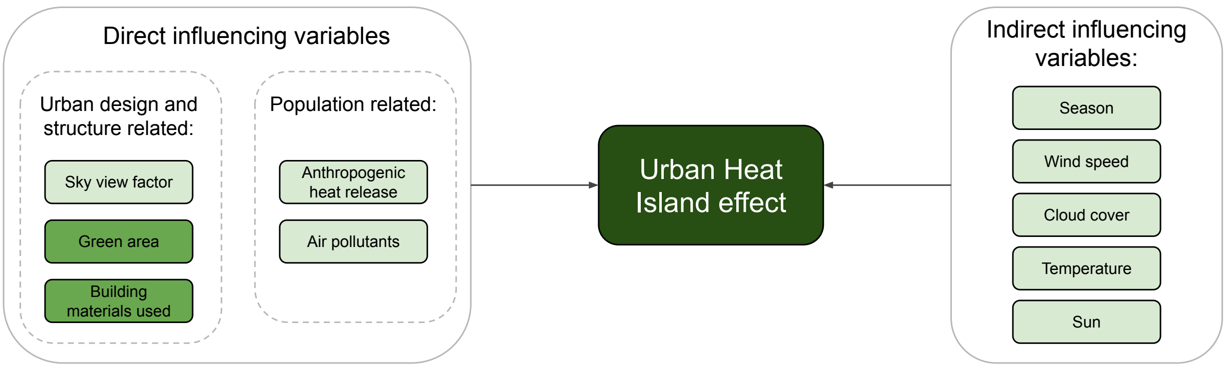


Figure 2.2: Variables influencing the Urban Heat Island effect *(Author's figure)*

Building materials

Each material in a certain construction has an albedo value, which represents the surface reflection of the material. This is the short wave radiation from the sun that is reflected from the surface on earth back into the atmosphere [51]. It can be measured with a device that first measures the incident sunlight, and shortly after that measures the reflected radiation. The albedo value is calculated by dividing the second measured value, the reflected radiation, by the first value, the incident radiation, leading to a value between 0 and 1. A surface with a low albedo will absorb most of the short-wave solar radiation, which is transferred into heat during the night. Materials with a higher albedo remain cooler when exposed to solar energy [48]. Research found that by changing the urban albedo, a decrease can be achieved of 2 °C air temperature and 50% of the resident cooling demand [35].

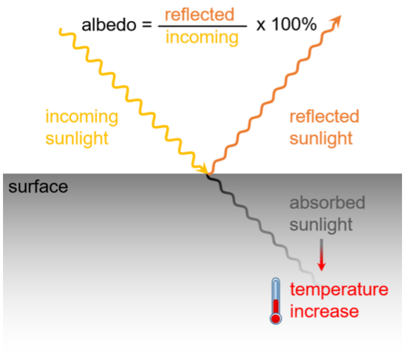


Figure 2.3: The meaning of albedo [2]

The influence of the type of building materials used is significant on the temperature. Asphalt and concrete, most commonly used building materials in urban areas, have a low albedo. The albedo of asphalt is 0.1 and of concrete is 0.3-0.4 [48]. At roofs often tar or bitumen is used, that have an albedo of 0.1-0.2 [52]. Researchers have experimented with several mitigation strategies for the Urban Heat Island effect, one of them is the "cool pavement effect" [48]. The road material is changed to increase the albedo, this could be from asphalt to a light-coloured concrete. This leads to less heat storage in the ground and more short wave radiation that is reflected, with a maximum ground surface temperature reduction of 7.9 °C [48]. An extra benefit that will result from this mitigation strategy is that the temperature of a pavement will affects its durability and performance on the long run [53]. Another mitigation strategy is "cool roofs", which means that the material of a roof is changed to a material with a higher albedo, or the roof is painted with a cool coating that will increase the radiation reflection. This leads to a reduction of the indoor temperature, especially in the rooms under the roof, and lowers the energy consumption of the building since less cooling is needed [48].

Green area

Due to the loss of green area the Urban Heat Island effect is getting worse. This is because shade is provided by trees and vegetation, that will result in a lowering of the temperature, thereby reducing the needed cooling energy [35]. Green area also reduces the air temperature through evapotranspiration, a process that combines the water transfer due to evaporation of the soil and transpiration from the vegetation to the atmosphere, which is visualized in figure 2.4. Vegetation reflects more solar radiation, since it has a higher albedo, and it absorbs and radiates less heat. Covering the walls and roofs with plants and vegetation is one of the most effective ways to the mitigate the heat generating effects of surfaces of building materials [54]. Research found that due to vegetation a reduction in air temperature can be found of: 8 °C in Athens, 20 °C in Tokyo, and 5 °C in Singapore [48]. The predicted heat increase of 4 °C in the city of Manchester, United Kingdom, in the upcoming 80 years could be avoided by implementing 10% more of the urban green area [55]. This 10% of urban vegetation cover is already experimented with in several researches, Wang et al (2016) found that it could lead to a mean radiant temperature decrease of 8.3 °C at 15:00 pm [48]. Another important effect of green areas is the insulating properties, especially if the vegetation is on the walls or roofs of buildings [56]. Placing the appropriate type and amount of vegetation can lead to eminent results, namely 55 % of the home energy consumption can be saved [35].

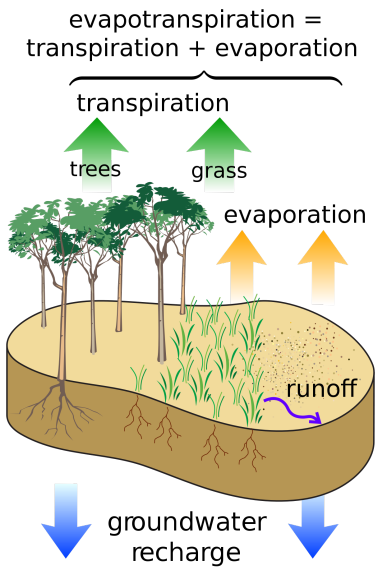


Figure 2.4: Evapotranspiration process [3]

2.1.2 Ecosystem services

An ecosystem can be considered as a set of species that interact in a local environment and function together to sustain life [57]. They provide us with ecosystem services, which is explained as *"the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life"* by Daily et al. (1997) [58]. An ecosystem service can be to maintain biodiversity or purify the air, but it can also provide ecosystem goods, such as timber and natural fibre [58]. Costanza et al. (1997) defined 17 ecosystem services that can be found on earth nowadays, some of them can be found in figure 2.5 [59]. Humanity has drawn benefits of ecosystem services for millennia, without causing any global disruptions. However, due to the industrialization and growing consumption this has changed. The presence of humans on earth can be felt virtually everywhere, on biological, chemical and physical levels [58]. Moreover, this leads to the disruption and loss of ecosystems, which has a severe effect on the surrounding environment. It seems that the values that ecosystem services provide mankind are only discovered after their loss. Deforestation has led to flooding, showing that roots are able to hold water, and the thinning of the ozone layer in the stratosphere has shown its property to screen out harmful ultra violet light [58]. It is likely that as human impact on earth intensifies, more ecosystem services will be discovered, and society will value the services that nature provides us with even more.

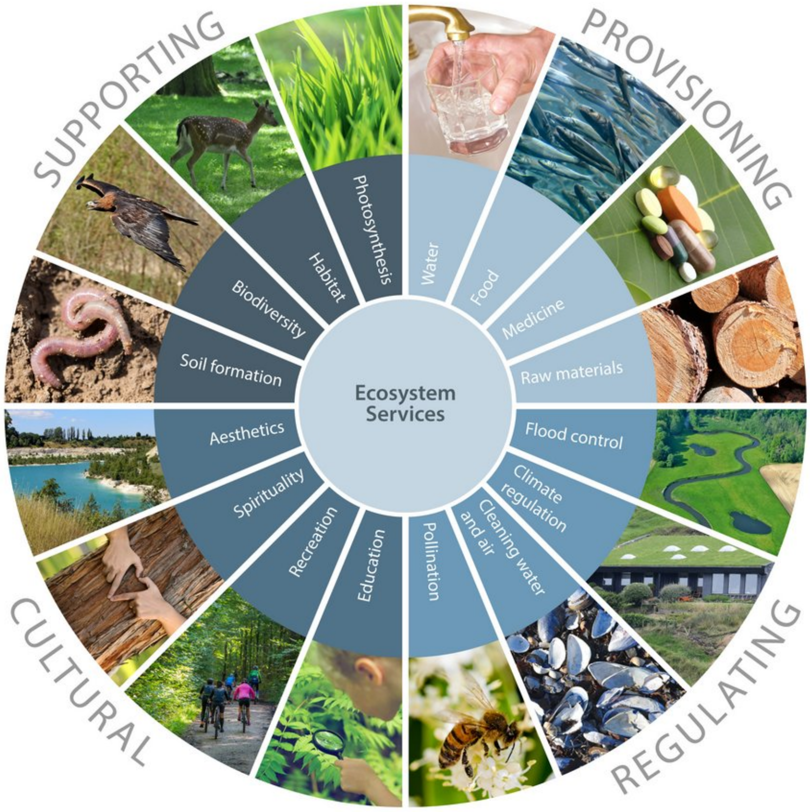


Figure 2.5: Ecosystem services [4]

Practically all existing ecosystems on earth have been influenced, changed or even destroyed by humanity. To mitigate this loss of ecosystems and their services, artificial ecosystems can be created deliberately in cities. This will take urban planning to the next level, by not only creating spaces for humans, but also for organisms and vegetation. Although natural formed ecosystems will provide most value, these artificial man-made ecosystems can be created to provide urban areas with ecosystem services and goods. Bolund et al. (1999) describe multiple ways in which ecosystems in urban areas can be formed, such as street trees, lawns, parks, and urban forests [60]. Green roofs and facades will contribute to ecosystems in their close environment, and therefore help provide ecosystem services, such as air filtering, regulation of the micro-climate, reduction of noise, rainwater drainage and aesthetic value [60].

2.2 Future cities

Now that some of the city problems are known, how should cities be designed to incorporate the needs of its future residents? There are several ways in which this a sustainable city design can be translated. An urban planning concept that has gained attention is that of the 'smart compact city' [40]. It promotes a high-density city with mixed land use functions, and has an efficient public transport system. Its residents are encouraged to walk or take their bike, and the city should be compact enough to provide social interaction. All of these actions will diminish harmful emissions from traffic and reduce the energy consumption. Moreover, due to more efficient use of space less infrastructure is required per capita [61]. Furthermore the efficient land use in the dense urban area will provide enough space outside the city for nature.

The World Health Organization has made a document that provides a list of action points for governments and local councils to make their cities more sustainable [33]. These action points will provide a better public health, and make cities more suitable for human life on physical and mental level. One of these action points is that there should be a sufficient amount of green space per inhabitant, with a minimum of 9 m^2 and an ideal value of 50 m^2 [32]. This will create value on multiple levels, since it can provide recreational benefits, social interaction, and improve city aesthetics.

It seems that several environmental problems in cities nowadays could be mitigated by incorporating more green in urban areas. Furthermore this is actually necessary for the development of sustainable cities and reaching this minimum of 9 m^2 of green area per capita [33]. More green in city areas can be achieved by adding parks, lawns and street trees, although this may seem contradictory with the 'smart compact city' concept. However, this is not necessarily the case, because there are several greening solutions that don't require much space and urban planning. Therefore a combination can be made between a green city and the 'smart compact city', creating a new view: **the Green Compact City** [40].

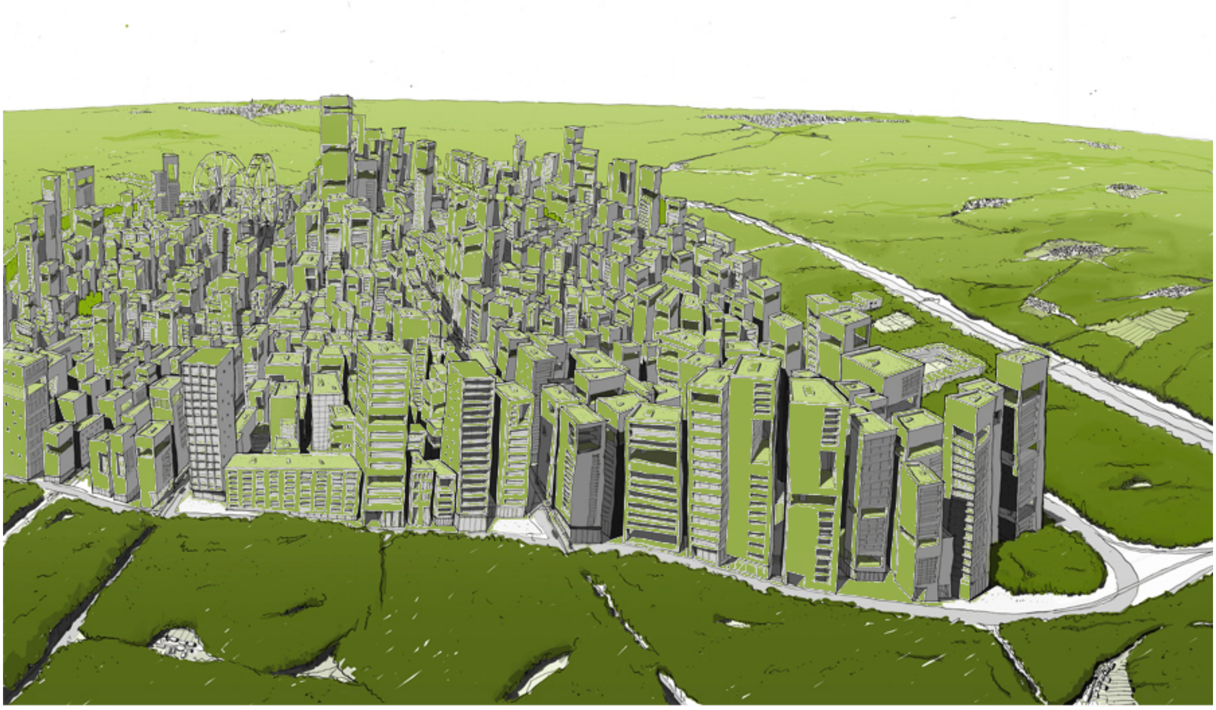


Figure 2.6: A green compact city [5] *(Altered by author)*

2.3 The Green Compact City

In the Green Compact City safe spacing greening is required, which can be satisfied by the greening of roofs and facades. This can be used in the existing built environment as well as in new construction plans. There are already several ways to make roofs and walls contain more vegetation, such as Living Wall Systems or rooted systems in the ground that climb up walls [37]. However in this research a new kind of greening technique will be investigated, namely the growth of mosses on concrete. This can lead to more green in dense urban areas in a cheap and efficient way with little maintenance [21]. Due to the low weight of mosses and the absence of roots in the concrete that could penetrate the structure and damage it, moss concrete is a promising solution that could provide the greening of urban areas [56].

Spontaneous abundant moss growth on young concrete structures can actually already be observed in practice, however this is often unintentional and unwanted, and is seen as the degradation of the concrete [29]. A better understanding of why spontaneous moss growth occurs on some constructions while it does not on others can help to intentionally design green concrete structures, and eliminate unwanted spontaneous moss growth on concrete.

The upcoming chapter is devoted to explaining the nature of concrete and some of its properties that are of interest for this thesis. In chapter 4 *Moss concrete* on page 33 an in depth literature study will be executed on the properties of moss concrete.

Chapter 3

Concrete

To stimulate moss growth on concrete an understanding of the material concrete is needed. In our modern society concrete is one of the key ingredients that we literally and figuratively build on. There are uncountable concrete buildings that people live and work in, the public and private transport is facilitated by concrete roads and bridges, concrete dams contain our water reservoirs and airplanes are able to land on concrete airstrips. Although this is only a fraction of where we can find concrete in our world today, concrete is taken for granted by the majority. This is a shame since concrete has led us to some of the most amazing achievements in our modern civilization, but it also led the Roman empire to their flourishing times. Concrete is a derivative of the latin word "Concretus" which can be translated to "let's grow together" [62].

In this research concrete is investigated as potential means for facilitating green walls and roofs. The upcoming chapter starts with a general exploration of concrete as a building material, the components that it constituents, the hydration process and the effect of curing. This is followed by an in-depth investigation of relevant properties of concrete that will contribute to the knowledge needed for moss growth on concrete. Since this moss growth will be stimulated on the surface of concrete, the porosity, permeability and water retaining capacity of the cover zone is of importance. The durability, sustainability and degradation mechanisms of hardened concrete will influence the design of moss concrete, therefore these are included in this literature study.

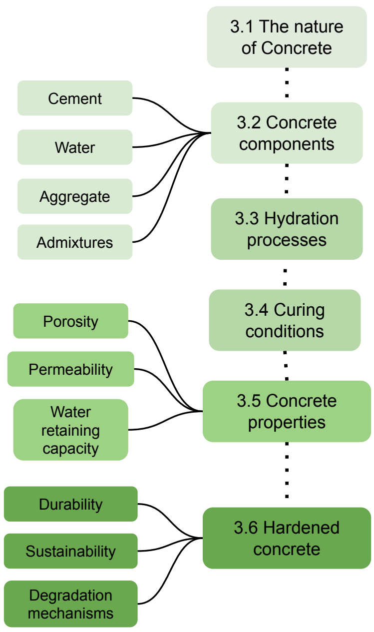


Figure 3.1: Outline of chapter 3 *(Author's figure)*

3.1 The nature of concrete

Concrete consists of multiple ingredients and is therefore a composite material. It consist of a filler, which can be a fine or coarse aggregate, and a hard binder that fills the empty space between the filler material and glues it together. This binder is often referred to as the matrix, and consists of cement and water that together form a hydraulic reaction [63]. The term "cement" is used in general and can consist of different ingredients. In table 3.1 the definition of concrete and its constituents can be found. In contrast to table 3.1, to the concrete mix manufactured nowadays several admixtures can be added, depending on the wanted properties and characteristics of the concrete. Some examples are air entrainers, accelerators, retarders and water entrainers, which will be explained in section 3.2.3 *Admixtures* on page 17

The present consumption of concrete is in the order of 12 billion tonnes every year [64]. The yearly use of concrete in the Netherlands nowadays is around 13 million m^3 each year [65]. There are heaps of advantages to the use of concrete, making it the second most consumed material after water [64]. Some of the advantages of using concrete as a building material are that it is economical attractive, durable, energy efficient, fire resistant, can be made on-site and has the ability to be casted in any desirable shape or form [62].

Name	Filler	Binder
Concrete	Fine and coarse aggregate	Cement paste
Mortar	Fine aggregate	Cement paste
Cement paste	-	Water and Cement

Table 3.1: Concrete definitions

Although this seems like an endless list of positive points, there are of course some drawbacks. Due to the on-site casting it is not always possible to control the quality of concrete, which can lead to major durability problems in later stages. Another problem is that due to the heterogeneity of concrete and its reactive nature concrete is vulnerable for several degradation mechanisms, which will be further explained in section 3.6.3 *Degradation mechanisms* on page 30 [66]. Some drawbacks of concrete as a structural material are the low tensile strength, the low ductility and the low strength-to-weight ratio. Structural engineers are aware of these drawbacks, and have to compensate for them by using suitable designs. This has led to the extended use of reinforced concrete, and to some new developments nowadays like fibre-reinforced concrete, self healing concrete and lightweight concrete [64].

3.2 Concrete components

In this section the components that make up concrete will be discussed. The types of cement, water, aggregates and admixtures that are used in concrete will be elaborated.

3.2.1 Cement

After the ancient Romans invented their so called 'Concretus', this material characterised by a hydraulic reaction fell into disuse for a long time after the roman empire had fallen [63]. It was only in 1824 that our first modern day cement type was founded and patented by Joseph Aspdin, and named "Portland cement" [67].

There are several types of cement available that differ in constitution, properties and performance. Portland cement is made up almost entirely of an ingredient named clinker. However, the amount of clinker varies per cement type, as can be seen in figure 3.2. Nowadays it is common to replace a part of this clinker by another type of binder. There are several reasons for this, but a major one is the polluting production process of clinker. This is further discussed in section 3.6.1 *Sustainability* on page 29.

Since concrete is such a widely used product, changing and reducing this harmful production process of clinker is high on the agenda. One alternative is to replace clinker by supplementary cementitious materials, like fly ash, silica fume or blast furnace slag [68]. An advantage of these alternative binders is that they are waste products of other sectors, and therefore their harmful emissions and polluting production processes can be accounted for, on paper, by these other sectors [69]. An schematic overview of cement types found in EN 197-1 and their composition can be found in figure 3.2 [6]. To form high quality cement, raw materials of an adequate purity and an uniform composition should be used [62].

Main types	Notation of the 27 products (types of common cement)		Composition (percentage by mass[a])										
			Main constituents										Minor additional constituents
			Clinker	Blast-furnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone		
						natural	natural calcined	siliceous	calca-reous				
			K	S	D[b]	P	Q	V	W	T	L	LL	
CEM I	Portland cement	CEM I	95-100	–	–	–	–	–	–	–	–	–	0-5
CEM II	Portland-slag cement	CEM II/A-S	80-94	6-20	–	–	–	–	–	–	–	–	0-5
		CEM II/B-S	65-79	21-35	–	–	–	–	–	–	–	–	0-5
	Portland-silica fume cement	CEM II/A-D	90-94	–	6-10	–	–	–	–	–	–	–	0-5
	Portland-pozzolana cement	CEM II/A-P	80-94	–	–	6-20	–	–	–	–	–	–	0-5
		CEM II/B-P	65-79	–	–	21-35	–	–	–	–	–	–	0-5
		CEM II/A-Q	80-94	–	–	–	6-20	–	–	–	–	–	0-5
		CEM II/B-Q	65-79	–	–	–	21-35	–	–	–	–	–	0-5
	Portland-fly ash cement	CEM II/A-V	80-94	–	–	–	–	6-20	–	–	–	–	0-5
		CEM II/B-V	65-79	–	–	–	–	21-35	–	–	–	–	0-5
		CEM II/A-W	80-94	–	–	–	–	–	6-20	–	–	–	0-5
		CEM II/B-W	65-79	–	–	–	–	–	21-35	–	–	–	0-5
	Portland-burnt shale cement	CEM II/A-T	80-94	–	–	–	–	–	–	6-20	–	–	0-5
		CEM II/B-T	65-79	–	–	–	–	–	–	21-35	–	–	0-5
	Portland-limestone cement	CEM II/A-L	80-94	–	–	–	–	–	–	–	6-20	–	0-5
		CEM II/B-L	65-79	–	–	–	–	–	–	–	21-35	–	0-5
		CEM II/A-LL	80-94	–	–	–	–	–	–	–	–	6-20	0-5
		CEM II/B-LL	65-79	–	–	–	–	–	–	–	–	21-35	0-5
	Portland-composite cement[c]	CEM II/A-M	80-88	<------------ 12-20 ------------>									0-5
		CEM II/B-M	65-79	<------------ 21-35 ------------>									
CEM III	Blast furnace cement	CEM III/A	35-64	36-65	–	–	–	–	–	–	–	–	0-5
		CEM III/B	20-34	66-80	–	–	–	–	–	–	–	–	0-5
		CEM III/C	5-19	81-95	–	–	–	–	–	–	–	–	0-5
CEM IV	Pozzolanic cement[c]	CEM IV/A	65-89	–	<------ 11-35 ------>					–	–	–	0-5
		CEM IV/B	45-64	–	<------ 36-55 ------>					–	–	–	0-5
CEM V	Composite cement[c]	CEM V/A	40-64	18-30	–	<------ 18-30 ------>			–	–	–	–	0-5
		CEM V/B	20-38	31-49	–	<------ 31-49 ------>			–	–	–	–	0-5

a The values in the table refer to the sum of the main and minor additional constituents.

b The proportion of silica fume is limited to 10 %.

c In Portland-composite cements CEM II/A-M and CEM II/B-M, in pozzolanic cements CEM IV/A and CEM IV/B and in composite cements CEM V/A and CEM V/B the main constituents other than clinker shall be declared by designation of the cement (for examples, see Clause 8).

Figure 3.2: The composition of the most common cement types according to EN 197-1 [6]

The cement types that can be used generic according to the European norm NEN-EN 206 and the Dutch supplement to that norm, the NEN 8005, are the following [70] [71]:

- Portland cement (CEM I)
- Portland-slag cement (CEM II/A-S and CEM II/B-S)
- Portland-fly ash cement (CEM II/A-V and CEM II/B-V)
- Portland-burnt shale cement (CEM II/B-T)
- Blast furnace cement (CEM III/A and CEM III/B)

From these cement types CEM I, CEM III/A and CEM III/B are most commonly used in the Netherlands.

Clinker

Portland cement, which is called CEM I in the Netherlands, is still the most commonly used cement type, and constitutes of argillaceous and calcareous materials, or any other material that contain iron oxides, aluminium and silicates [63]. These raw materials are mixed together and burned in a rotary kiln at clinkering temperature, and grinded to form clinker [62]. Portland cement exists almost entirely of this clinker. A schematic representation of this production process can be found in figure 3.3.

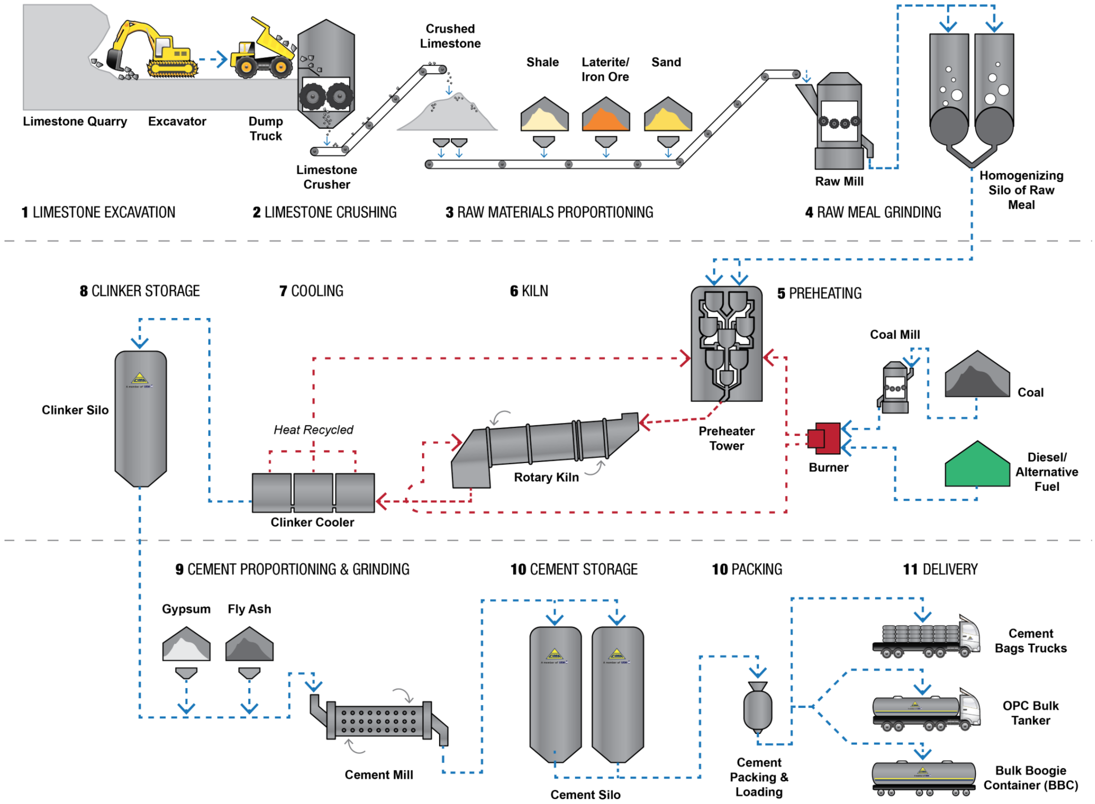


Figure 3.3: Production of clinker [7]

At the end of the production process a clinker with the following constituents is formed:

- C_3S - Tricalcium silicate
- C_2S - Dicalcium silicate
- C_3A - Tricalcium aluminates
- C_4AF - Calcium ferroaluminate

Gypsum is added at the end of the manufacturing process to control the setting time of concrete, which will be further explained in section 3.3 *Concrete hydration* on page 18.

- $C\underline{S}H_2$ - Gypsum

The meaning of abbreviations C, S, A, F, $\underline{S}$, H, and $\underline{C}$ can be found on page xv *Abbreviations*.

Alternative binders

Fly ash
Fly ash is a waste product from the electricity industry. In thermal power plants coal is burned, which releases gasses that contain fly ash. Fly ash has pozzolanic properties, meaning that it will harden in combination with water and calcium hydroxide (CH), which is further discussed in section 3.3.2 *Hydration of alternative binders* on page 20. The

advantage of using fly ash is that it leads to less waste products from the energy industry that must be disposed as land fill. Thereby, as explained in the previous section, it comes energy 'neutral' in the concrete life cycle, since the polluting properties are attributed to the energy industry on paper. In addition to being sustainable, fly ash can be beneficial to concrete is several ways. Fly ash consist of fine and smooth spherical particles, which results among others in a denser pore size distribution [72]. It contributes to the strength development of concrete, reduces the heat of hydration in mass concrete, and improves the workability [72]. Besides these qualities, fly ash can contribute to the protection against several degradation mechanisms, such as alkali-silica reactions and sulfate attack [72] [73]. This is further discussed in section 3.6.3 *Degradation mechanisms* on page 30.

In NEN-EN 197-1 and NEN-EN 450-1 the specifications of fly ash used in cement and concrete are given [74] [6]. There are two types of fly ash, namely siliceous fly ash (V), and calcareous fly ash (W). Siliceous fly ash (V) consists essentially of aluminium oxide (A) and reactive silicon dioxide (S). The content of reactive silicon dioxide (S) should be 25,0% or higher. The remaining part contains iron oxide (F) and other substances. The amount of reactive calcium oxide (C) should be less than 10,0 % by mass, and the content of free calcium oxide (C) should not exceed 1,0 % by mass. The second type of fly ash is calcereous (W), which consists mostly of reactive calcium oxide (C), Aluminium oxide (A), and reactive silicon dioxide (S). The portion of reactive calcium oxide (C) should be higher than 10,0 % by mass. The remaining part consists of iron oxide (F) and other compounds.

	Siliceous fly ash (V)	Calcareous fly ash (W)
Reactive calcium oxide (C)	≤ 10,0 %	≥ 10,0 %

Table 3.2: Fly ash constituents

Blast furnace slag
Blast furnace slag is a by-product of the steel industry. In the Netherlands, blast furnace slag cement has a large market share, and is used quite commonly and in a high dosage as clinker replacement [64]. It is received during the rapid cooling of molten slag, which is obtained when iron ore is molten in a blast furnace. Just like fly ash, blast furnace slag increases the workability of fresh concrete, and lowers the heat productions during hydration [64]. The microstructure will be denser when blast furnace slag is added, leading to an improved resistance against the penetration of harmful substances, which will be discussed in section 3.6.3 *Degradation mechanisms* on page 30. The strength development of blast furnace slag is slower compared to clinker, leading to a lower strength in the first couple of days. However, the strength will keep on increasing, after a month the strength can be higher than when clinker is used [64].

Blast furnace slag has hydraulic properties when activated properly and has pozzolanic properties in the second stage, which is further discussed in section 3.3.2 *Hydration of alternative binders* on page 20 [6]. It is common in the Netherlands to mix clinker and slag in the production process of cement before grinding, in contrary to the rest of the world [64]. According to NEN-EN 197-1 and NEN 8005 al least 2/3 of the mass of Blast furnace slag should be the sum of calcium oxide (C), magnesium oxide (M), and silicon dioxide (S) [6] [70]. The remaining mass contains aluminium oxide (A) and small portions of other substances. The following formula for the masses of calcium oxide, magnesium oxide, and silicon dioxide must be satisfied:

$$\frac{C+M}{S} \geq 1 \tag{3.1}$$

C = calcium oxide, M = magnesium oxide, S = silicon dioxide

3.2.2 Water

To receive a hydraulic reaction cement and water should be mixed. The used water must conform to the specifications given in NEN-EN 1008 [75]. Water in concrete is a friend and a foe, it provides the hydraulic reaction and the workability that is needed to cast concrete, but on the other hand water will result in pores in the concrete that lower the strength. Therefore, the amount of water in a concrete mix design should be decided carefully. In section 3.3 *Concrete hydration* on page 18 the role of water in the concrete hydration process is explained.

3.2.3 Admixtures

Admixtures are added to the concrete during the mixing process and can modify properties in the mixing stage as well as in the hardened state. The admixture should be less than 5 % of the mass of the cement content [76]. The following admixtures can be used in concrete, according to NEN-EN 934-2 [76]:

Water-reducers: Plasticizers and Super-plasticizers enable a reduction in the water content of a concrete mix, without affecting the consistence. This leads to a higher strength at the same workability. It can also increase the workability, for easier placing in inaccessible locations, without affecting the water content. Plasticizers can lead to a reduction of the water-to-cement ratio of around 25 %, Super-plasticizers enable a 40 % reduction of the water-to-cement ratio [64].

Set-accelerators will decrease the time that is needed to go from the plastic to the rigid state, thereby specifically reducing the setting time. This can be used for cold climates, which will be further discussed in section 3.4 *Concrete curing* on page 23.

Hardening accelerators will accelerate the hardening process, thereby increasing the rate of early strength development of the concrete mix. This can be with or without affecting the setting time, and is often used in cold climates. This is further elaborated in section 3.4 *Concrete curing* on page 23.

Water retainers reduce the amount of water that is lost during bleeding [64].

Air entrainers allow a controlled amount of uniformly distributed small air bubbles in the mixer, that will remain in the concrete after hardening. It creates a more workable concrete, while it reduces segregation and bleeding. Air entrained in the concrete leads to a high resistance against freeze-thaw cycles, thereby increasing the durability of the concrete, which is discussed in section 3.6.3 *Degradation mechanisms* on page 30.

Set retarders extend the time that it takes the mix to transition from the plastic to the rigid state. The chemical reaction that occurs to start the setting process is delayed. This can be used when concrete is casted in a climate with elevated temperatures, which will be further discussed in section 3.4 *Concrete curing* on page 23.

3.2.4 Aggregate

In NEN 8005 it is specified that aggregate used in concrete should have a mass of at least 2000 kg/m^3 and should satisfy the requirements specified in NEN-EN 12620 and the dutch supplement to this, NEN 5905 [70] [77] [78]. Aggregate is divided in two types, coarse aggregate and fine aggregate, which is usually sand. Coarse aggregate can have several shapes and textures, such as rounded or angular, that will influence the fresh and hardened properties of concrete. The shape and texture of fine aggregate influences the water requirement of a concrete mix. Nowadays recycled aggregates from crushed concrete and asphalt are being used, which should satisfy the requirements of NEN 5905 and NEN 8005 [70] [78]. In the Netherlands it is quite common to use river grind as an aggregate.

3.3 Concrete hydration processes

When water and cement are combined a hydraulic reaction will occur. In this section this hydration process of concrete will be discussed. Since the hydration of clinker is different from the hydration of alternative binders, these are treated separately.

3.3.1 Clinker hydration

Clinker is hydraulic, meaning that silicates and aluminates will react direcly with water to form hydration products. Over time, these hydration products together develop in a hard mass, that is called the cement paste [63]. When water (H) is added to clinker, the C_3S and C_2S that are present in clinker will react with water to form calcium silicate hydrates (CSH) via the following reactions [64]:

$$2C_3S + 6H \longrightarrow CSH + 3CH \tag{3.2}$$

$$2C_2S + 4H \longrightarrow CSH + CH \tag{3.3}$$

The reactions of C_3A and C_4AF depend on the availability of gypsum, $C\underline{S}H_2$, and the formed ettringite, $C_6A\underline{S}_3H_{32}$.

1. *When there is enough gypsum:*

$$C_3A + 3C\underline{S}H_2 + 26H \longrightarrow C_6A\underline{S}_3H_{32} \quad (3.4)$$

$$2C_4AF + 3C\underline{S}H_2 + 30H \longrightarrow C_6A\underline{S}_3H_{32} + CH + FH_3 \quad (3.5)$$

2. *If all the gypsum is used, but there is still ettringite available:*

$$2C_3A + C_6A\underline{S}_3H_{32} + 4H \longrightarrow 3C_4A\underline{S}H_{12} \quad (3.6)$$

$$2C_4AF + C_6A\underline{S}_3H_{32} + 12H \longrightarrow 3C_4A\underline{S}H_{12} + 2CH + 2FH_3 \quad (3.7)$$

3. *If both gypsum and ettringite have been used*

$$2C_3A + 6H \longrightarrow C_3AH_6 \quad (3.8)$$

$$C_4AF + 10H \longrightarrow C_3AH_6 + CH + FH_3 \quad (3.9)$$

C_3S and C_2S are the most important components for the strength development. C_3S will ensure that there is an early strength development over the first four weeks, while C_2S will contribute to strength development after four weeks [62].

Hydration stages of clinker

The hydration process of the clinker grains is an exothermic reaction. The heat released during the reactions of C_3S, C_2S, C_3A, and C_4AF, described above, can be measured by an isothermal calorimeter. This gives a characteristic rate of heat evolution that can be seen in figure 3.4 [62]. The hydration process can be divided into five stages, based on their rate of heat release identified in figure 3.4 [64].

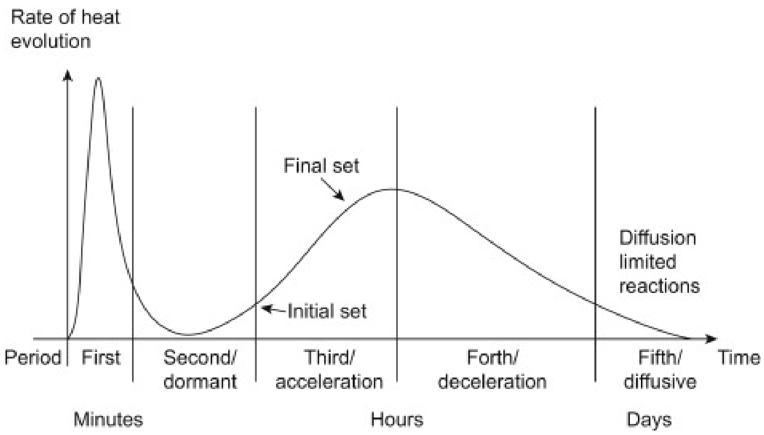


Figure 3.4: Stages of hydration [8]

Stage I - The initial hydrolysis
In this period the cement grains will have their first contact with water, and start to react. The clinker components will dissolute in the water, and calcium aluminates (C_3A) will be the first one to react. To control this reaction and avoid too early setting of the concrete mix gypsum ($C\underline{S}H_2$) is added [62]. Therefore the first peak that can be seen in figure 3.4 is due to the reaction of calcium aluminates C_3A and gypsum ($C\underline{S}H_2$) that will form ettringite ($C_6A\underline{S}_3H_{32}$), which can be seen in formula 3.4. Due to the reaction products that are formed around the unhydrated cement grains the hydration reaction is slowed down.

Stage II - The induction period
In this period the hydration products that form a protective layer on the surface of the unhydrated cement grain prevent any further reactions taking place. Since concrete is now in a plastic state it can be transported from the mixing unit into the formwork.

Stage III - The acceleration stage
At the beginning of this stage the protective layer around the unhydrated cement grains breaks open, and the setting of concrete starts. This is the stage where the concrete will develop from a plastic into a more rigid state, that is followed by the hardening process that contributes to the development of useful and measurable strength [62]. C_3S and C_2S will start to react rapidly with water, forming CSH and CH which can be seen in reaction formulas 3.2 and 3.3 on page 18. The reactions of C_3A and gypsum will continue to form ettringite as long as there is still gypsum present, otherwise the reactions seen in formula 3.6 and formula 3.7 will take place. At the end of this period the reaction speed will be at its maximum rate. By this time the final set has passed, and the hardening process will start. The hydration products of a cement mix that consist of pure clinker (CEM I) precipitate close to the cement grain, as is illustrated in figure 3.5. This will eventually lead to relatively more capillary pores in the hardened cement paste compared to the hydration reaction that will occur when there are alternative binders present in the cement mix, which is explained in the section 3.3.2 *Hydration of alternative binders* below.

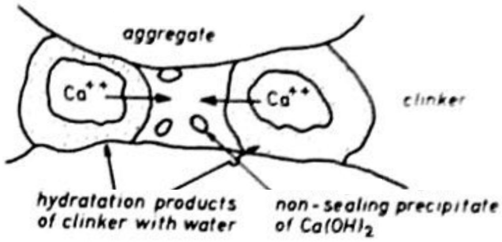


Figure 3.5: Hydration of clinker [9] *(Altered by author)*

Stage IV - The deceleration stage
This stage starts at the deceleration of the reaction rate. Due to the formed hydration products around the unhydrated cement grains the rate of the reaction is slowed down gradually. A lot of hydration products are still formed in this stage. The rate of early strength gain is determined by this stage, which happens in the first 12-24 hours [62].

Stage V - The diffusion stage
At some point the layer around the unhydrated cement grains enables only a diffusion controlled hydration reaction. The hydration reaction will keep on going but also keeps on slowing down, thereby reaching a steady state. The rate of later strength development is defined by this last stage.

3.3.2 Hydration of alternative binders

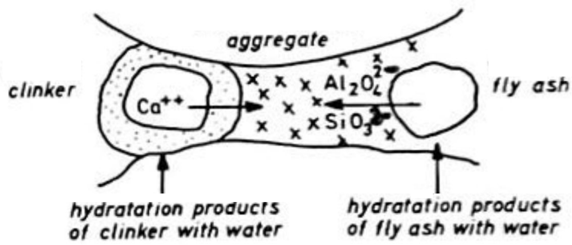


Figure 3.6: Hydration of clinker and fly ash [9] *(Altered by author)*

Fly ash
Fly ash is a waste product from the electricity industry. It has pozzolanic properties, meaning that a pozzolanic reaction occurs in the second stage when fly ash is in contact with water and calcium hydroxide (CH) [62]. The reactions are shown simplified in formula 3.11. Since calcium hydroxide is needed for the second stage reaction, fly ash needs to be activated. Therefore a part of clinker is usually present in cement types that contain fly ash [6]. The clinker will form an alkaline pore solution with plenty of calcium hydroxide (CH) that can be used for the pozzolanic reaction of fly ash. This leads to less calcium hydroxide (CH) available in the pore solution, and therefore a reduction in pH. Since the reaction of clinker and fly ash takes place in the pore solution, the hydration products will precipitate between the cement grains, thereby lowering the amount of capillary pores and creating a dense microstructure with an increased amount of gelpores, which is visualised in figure 3.6.

$$C_3S + H \longrightarrow CSH + CH \tag{3.10}$$

$$FlyAsh + CH + H \longrightarrow CSH \tag{3.11}$$

Blast furnace slag
Blast furnace slag is a by-product of the steel production industry. Unlike fly ash it is not only pozzolanic, but also latent-hydraulic, meaning that it only needs water to react. However, this reaction is relatively slow and can be speeded up when the pH is increased by an activator, like calcium hydroxide (CH). The increased pH will break down the glass structure of blast furnace slag, and will allow the reaction to be faster [64]. This calcium hydroxide (CH) usually comes from the reaction of clinker and water, therefore cement with a combination of blast furnace slag with clinker is quite common (CEM III/B) [6]. Blast furnace slag has a pozzolanic reaction in the second stage [64], a simplified version of the reactions that take place can be seen in formula 3.12 and 3.13. The reaction between the slag particles and clinker products will partly take place in the pore solution, thereby creating a dense pore structure and lowering the amount of capillary pores and increasing the amount of gel pores, which is visualised in figure 3.7. The pore solution that results from this cement is less alkaline than from a cement mix with a high content of clinker. This is can lead to several degradation mechanisms, which will be discussed in section 3.6.3 *Degradation mechanisms* on page 30.

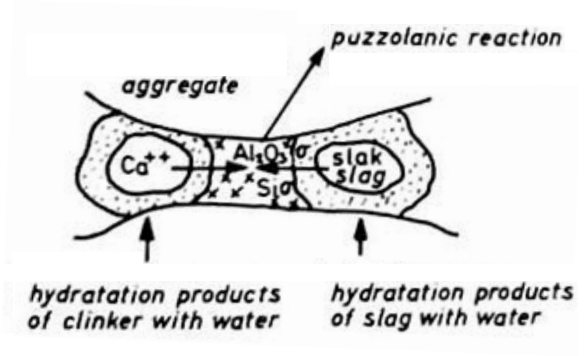


Figure 3.7: Hydration of clinker and blast furnace slag [9] *(Altered by author)*

$$C_3S + H \longrightarrow CSH + CH \quad (3.12)$$

$$BlastFurnanceSlag + CH + H \longrightarrow CSH \quad (3.13)$$

3.3.3 Voids in the hydrating cement paste

The hydrating cement paste has in addition to solids several types of voids that will influence the properties of the concrete. In figure 3.8 the types and sizes of voids that are found in hydrating cement paste and in several solid phases are illustrated [10]. The kind of voids that exist in concrete and their size are influenced by the mix design, the setting conditions and the curing conditions, this will be further elaborated in section 3.4 *Concrete curing* on page 23.

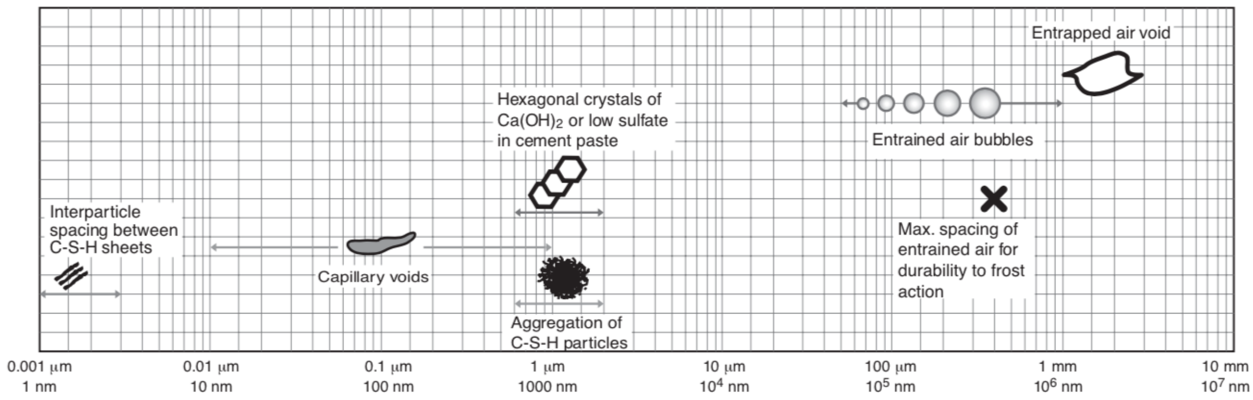


Figure 3.8: Voids in the hydrating cement paste [10]

Interlayer space in CSH
This is the space that is in between the calcium silicate hydrates sheets (CSH) . According to Powers the width of this space is 18 Å and accounts for 28 % of the porosity in solid calcium silicate hydrates (CSH). However, the model of Feldman and Sereda suggests that there is a variation of 5 - 25 Å of the space width [79] [10]. For both models the void size is too small to have a negative effect on the permeability and strength of the hydrated cement paste. Water inside these voids is called interlayer water, which is discussed in section 3.3.4 on page *Water in the hydrating cement paste* on page 22 .

Capillary voids
The capillary voids represent the space inside the hydrating cement paste that is not filled with solid components of cement or the hydration products, and are often irregular shaped [10]. Although the total volume of a water-cement mixture will stay the same during hydration, the density of the hydration products is considerably lower than that of unhydrated cement grains. 1 cm^3 of cement on complete hydration, needs approximately 2.2 cm^3 of space for the hydration products [64]. In low water-cement ratio mixes, these capillary voids may range from 10 - 50 nm. However, in pastes with a high water-cement ratio, the capillary voids may become as large as 3 - 5 μm. This is actually the case when the casted concrete is perfectly cured. Insufficient curing will result in an elevated amount of capillary pores, which is detrimental for concrete. In section 3.4 *Concrete curing* on page 23 this will be discussed.

Air voids
The air voids that are present in the hydrating cement paste are larger than the capillary voids, which is illustrated in figure 3.8, and can adversely affect the strength [10]. Usually during concrete mixing a small amount of air gets trapped in the mix, which is called entrapped air. These voids are usually irregular shaped and may become as large as 3 mm. When air entraining admixtures are added to the concrete mix, described in section 3.2.3 *Admixtures* on page 17, spherical entrained air bubbles are formed that can range from 50 - 200 μm.

3.3.4 Water in the hydrating cement paste

There are several forms of water present in the hydrating cement paste. The classification is based one the difficulty or easy with which the water can be removed from the hydrating cement paste. The types of water that exist in concrete are illustrated in figure 3.9, based on the Feldman-Sereda model [10].

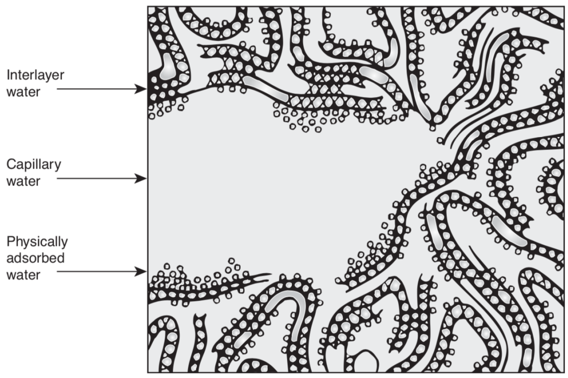


Figure 3.9: Types of water in the cement paste [10]

Capillary water
This water is present in voids that are larger than about *5 nm*, and can be seen as bulk water. Removal of water in the larger voids, > 50 *nm* won't cause any volume changes. Water held in small capillaries, 5 - 50 *nm*, can cause shrinkage of the system when removed, which is illustrated in figure 3.10 [10].

Adsorbed water
Water molecules that are located in the gel pores of the cement paste and are adsorbed on the surface of calcium silicate hydrates (CSH) are called absorbed water. Up to six layers of water molecules can be physically held by hydrogen bonding, which is 15 Å thick. When the relative humidity in the hydrated cement paste becomes lower than 30% this bonding force disappears, and adsorbed water is lost causing shrinkage of the hydrated cement paste [10].

Interlayer water
This is the water that is within the calcium silicate hydrates structure. There is a mono-molecular water layer between the formed strings of CSH, which can be seen in figure 3.9. This interlayer water is held strongly by hydrogen bonding. When the relative humidity becomes below 11 % this hydrogen bond is lost, and the structure will shrink strongly [10].

Chemically bound water
This water is bound in the microstructure of several hydration products by chemical reactions. The loss of this water

will not occur due to evaporation, but the water will decompose due to heating.

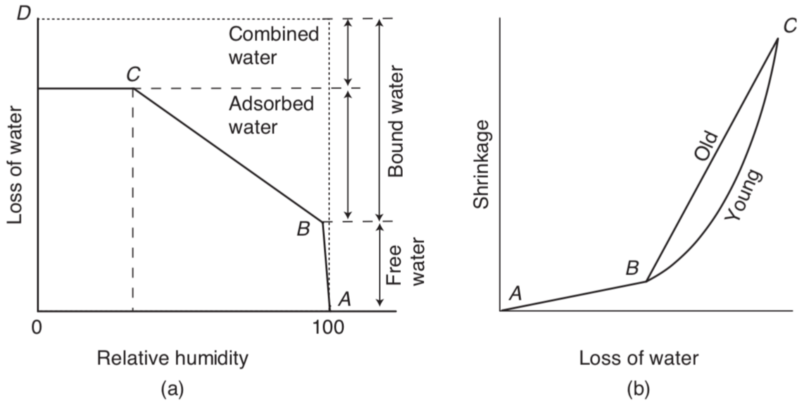


Figure 3.10: Loss of water as a function of the relative humidity and shrinkage [10]

3.4 Concrete curing

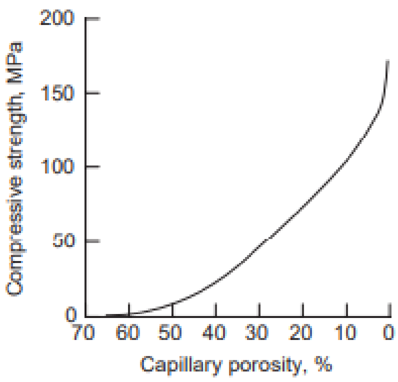


Figure 3.11: Relation porosity-strength [10]

To develop concrete with optimal properties, the casted concrete mix should be properly cured [62]. Proper curing means that all factors that promote the hydration process, namely humidity conditions, time and the temperature, should be optimised [10]. To keep the hydration process going there should be enough moisture present. This will ensure that there are enough hydration products being formed to provide the wanted strength and durability. On the other hand too much water can be detrimental for concrete, because this surplus of water will have no cement left to react with at a certain point, causing the concrete to be more porous. This will cause problems for the strength development and durability. The relation between porosity and strength can be seen in figure 3.11. Improper concrete curing will lead to an elevated amount of capillary pores. This can have detrimental effects for the concrete properties, which will be discussed in section 3.5 *Concrete properties* on page 26.

Concrete with a low water-cement ratio will have little porosity which will result in a high strength. However, a low water-cement ratio may lead to self-desiccation because at a certain point little water is available to hydrate the cement grains, causing the hydration reaction to cease. This can occur for water-cement ratios that are lower than 0.42 [62]. Water-cement ratios that are above this threshold should in theory be able to completely hydrate. However, concrete will never completely hydrate because the thick layer of hydration products on the unhydrated cement grains will prevent reactions taking place, as is described in section 3.3 *Concrete hydration processes* on page 18. Proper curing will ensure that as much water as possible will react, and enable a minimal water loss during placement and curing. Water loss during curing can be due to bleeding and evaporation from the surface of the concrete, or because the aggregates inside the concrete absorb water [10].

3.4.1 Parameters affecting concrete curing

Some of the parameters that affect the curing of concrete are time, the internal and external relative humidity, and the temperature. For each parameter the mechanisms is described, and the positive or negative effect that it has on the hardening of concrete.

Time

The hardening process of concrete develops over time, making time a very important variable in the curing process. In the first couple of weeks most hydration products will be formed, that will fill voids in the hydrating cement paste leading to strength development, which is illustrated in figure 3.11. In the standards it is agreed that after 28 days of curing the strength will be tested, and that is the "strength" that is given to a certain concrete mix [11]. Of course this not the actual strength, since the hydration will continue, developing more strength over time, which can be seen in figure 3.12.

Humidity

The moisture present in the external and internal environment will influence the hydration process and curing of concrete. The external conditions will influence the rate of evaporation, such as the temperature, wind-speed and external relative humidity. The internal conditions of importance for the moisture content are the internal relative humidity, porosity and pore connectivity [80].

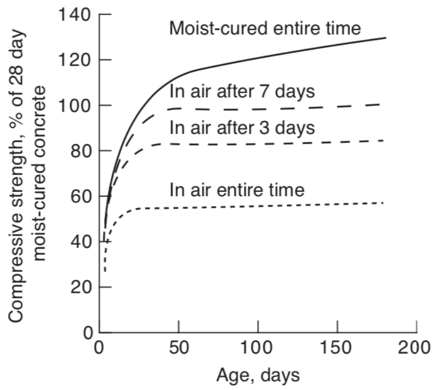


Figure 3.12: Effect of humidity conditions during curing on the strength [11]

Even when concrete is not fully saturated with water the hydration process will continue, because there is water present in the capillary pores. When the external relative humidity is lowered this water will evaporate, leaving little water inside the capillary pores. This will influence the water flow inside the pore system of concrete in the following way: water inside concrete will be used for the hydration of its local area and parts that hydrate more rapidly, like small cement grains, will become starved for water. This leads to a water flow from areas where there is abundantly water present to the starving parts [62]. When concrete is fully submerged in water, for example during water curing, a quick water flow is possible since there is abundantly water present. However, this flow will occur at a much lower velocity in a partly saturated system [62]. What this means is that concrete that is sealed to prevent the evaporation of water will hydrate more slowly than when water cured, since the velocity of the water flow inside the concrete will be lower. Therefore, the strength development will be more slowly in comparison to concrete that is submerged in water.

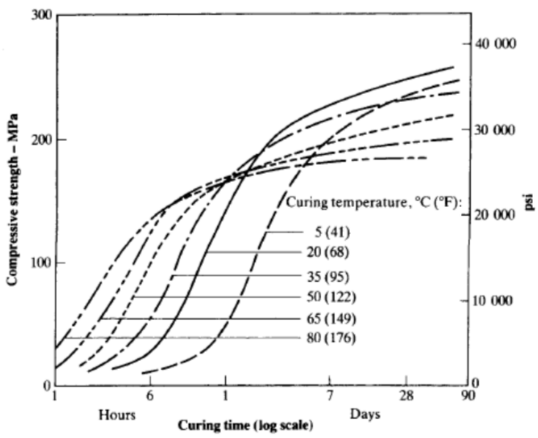


Figure 3.13: Effect of temperature on strength [10]

The external relative humidity will either prevent or stimulate the drying out of concrete in an early stage. When concrete is dried out the hydration reaction will cease, leaving the concrete with empty voids, and therefore a higher porosity. This effect is stimulated when there is more wind and the temperature is higher, leading to a higher evaporation rate that will ensure less water available for hydration. The effects of the external conditions during concrete curing on the compressive strength can be seen in figure 3.12 [10]. This shows that concrete submerged in water will have more hydration products and therefore a higher compressive strength.

Temperature

The outside temperature influences not only the evaporation speed, but also the hydration pace of the cement paste. At an elevated temperature the hydration speed will go up, creating more hydrated volume and giving the concrete an early age strength [64]. However, it ensures that the hydration products will grow less outward, creating a smaller hydrated area around the unhydrated cement grains. This means that although in the beginning the hydration is faster, it will result in a smaller volume of hydrated paste, and therefore in a higher porosity. Concrete that is hydrated at an elevated temperature will have less strength and more porosity in the long-term, illustrated in figure 3.13 [64].

3.4.2 Curing methods

To optimize the curing of concrete multiple methods are available. These methods aim to minimize the amount of evaporated water from the surface of concrete and enabling enough water available to keep the hydration reaction going.

Sealed curing

This means that the freshly casted concrete is sealed to prevent water from evaporating at the top layer [62]. This could be achieved by:

- *A curing compound* - this is a dispersion, meaning that it is a liquid that contains very fine globules that are solved in a carrier fluid, that will be spread over the cover of the concrete. The fine globules are the active substance in the curing compound, and will form a strong film layer on the concrete when the carrier fluid is evaporated, which is visualised in figure 3.14 [12]. The film layer prevents water from evaporating, thereby consolidating the hydration process.

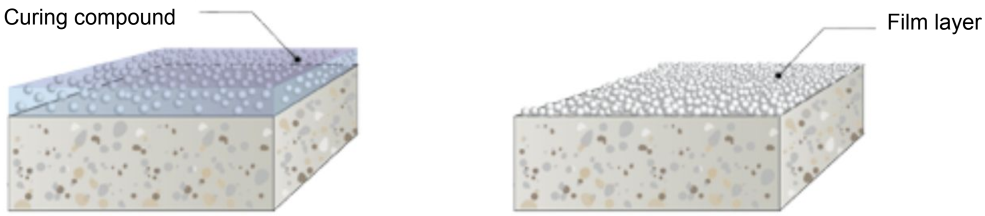


Figure 3.14: Application of a curing compound that results in a film layer [12] *(Altered by author)*

- *Plastic sheeting* - When the concrete surface has hardened sufficiently, it will be thoroughly wetted, after which the surface will be covered by plastic sheeting. Water that has been evaporated from the concrete is retained and condenses against the plastic sheeting, from which it is redistributed. The plastic sheets can be placed easily and are able to cover complex shapes. In summer they can be made white to reflect sunlight and reduce the heat absorption, while in winter they can be made black to increase the heat absorption.

Water curing

When concrete is water cured there will be a constant supply of water on top of the surface [62]. This could be achieved in multiple ways, some examples are:

- *Ponding* - maintaining a constant layer of water on top of the concrete
- *Spraying* - with a fine spray the concrete is being moisturized continuously
- *Saturated covers* - the concrete can be covered with absorbent material that can hold quantities of water to avoid evaporation, such as damp earth, sawdust, straw and sand. Periodic moisturising is needed to keep the layer wet, because it will dry out due to evaporation.

Cold climate curing

When concrete is cured in a cold climate, the low ambient temperature will retard the setting time. Since it is expensive to keep the formwork for a couple of days longer measures can be taken to prevent this. Covers can be added on top of the concrete to trap the generated heat from the reaction. Warm water can be added in the mixing mill to heat up the mixture. When the outside temperature is below 5 °C concrete can't be casted unless precautions are made.

Hot climate curing

At elevated temperatures there are several problems with concrete casting and curing. The workability will drop rapidly since the hydration reaction is accelerated, which can result in problems for pumping and placing the concrete in formwork. The water will evaporate from the surface of the concrete, leading to desiccation of the cover zone and thereby a lower quality of the concrete cover zone. The fresh concrete mix should be cooled to enable proper casting and curing. This can be done with water or by liquid nitrogen [64]. The climate in which concrete is casted will influence the time of day that the casting will start. In the Netherlands the unofficial rule in the construction industry is that casting will begin at 07:00 in the morning. However, in countries with a warmer climate the casting often starts around 19:00 at night, so when the casting is finished it will be in the middle of the night and the temperature will be lowest.

3.5 Concrete properties

The microstructure of concrete is determined by several factors, such as the water-cement ratio of the concrete mix, the type of cement being used, the curing conditions and the admixtures added to the concrete mixture [64]. The microstructure influences the properties of concrete in the mixing stage, the hardening phase, and its long term behaviour. The concrete properties will determine the performance of concrete, which is illustrated in figure 3.15. In this section the properties porosity, permeability, pore connectivity and water retaining capacity will be discussed.

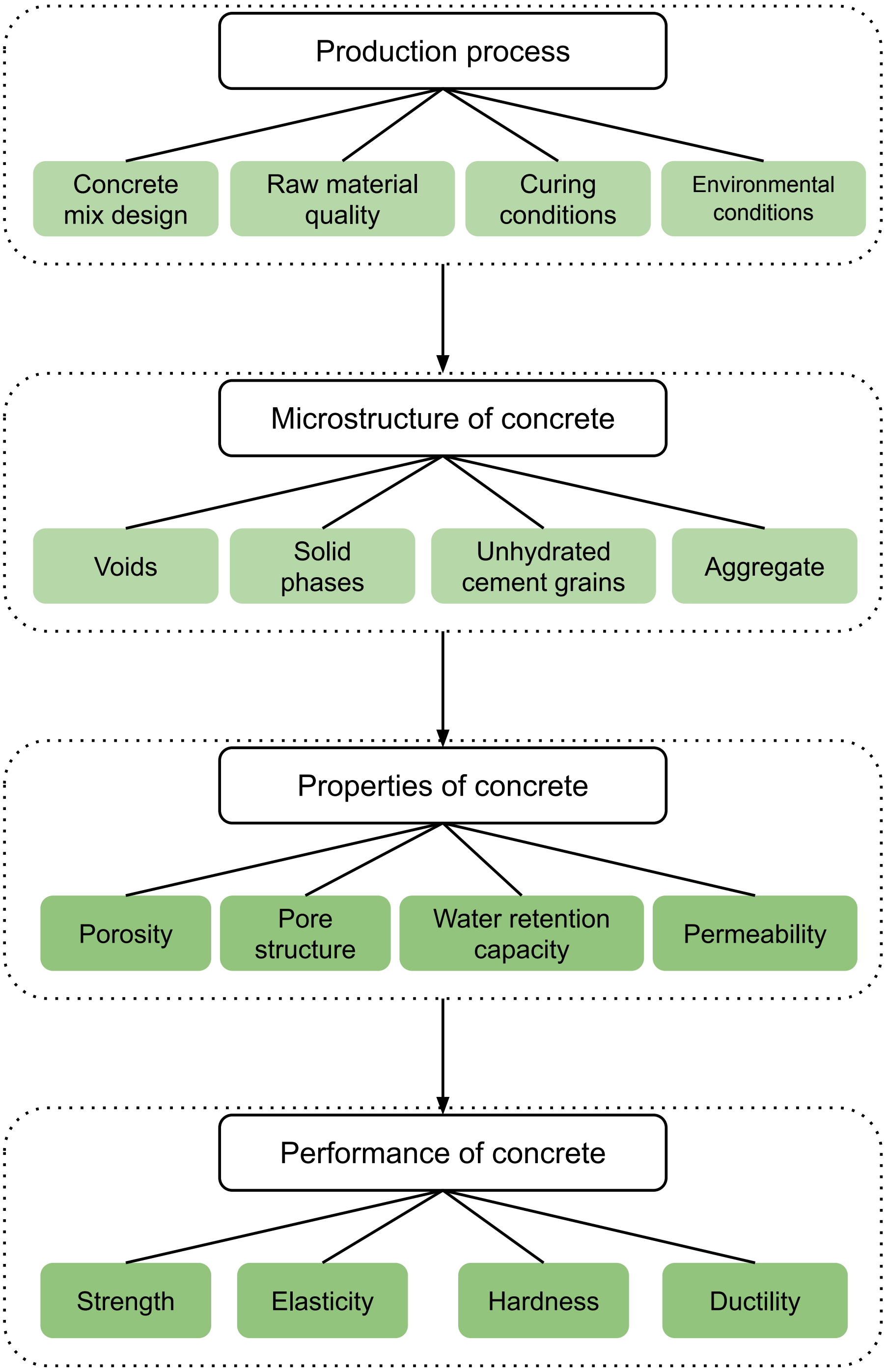


Figure 3.15: The effect of the process, microstructure, properties, and performance *(Author's figure)*

3.5.1 Porosity

The total volume of capillary voids inside the concrete, discussed in section 3.3.3 *Voids in the hydrating cement paste* on page 22, is called the porosity [10]. According to Powers [79], the initial porosity of a concrete mix can be calculated with formula 3.14. The porosity of a concrete mix will change over time, since the degree of hydration will influence the amount of solids and voids in the concrete. The actual porosity at a certain moment can be calculated by dividing the volume of capillary voids by the total volume of the initial amount of cement and water, illustrated in formula 3.15 [64].

$$p_{initial} = \frac{V_w}{V_w + V_c} \tag{3.14}$$

$$p = \frac{V_w - V_{gw} - V_{cw}}{V_w + V_c} \tag{3.15}$$

V_w = the volume of the initial amount of water added to the mix
V_{gw} = the amount of gel pore water
V_{cw} = the amount of chemical bound water
V_c = is the initial amount of cement added to the mixture

In fresh casted concrete the porosity is initially high, after which it will slowly decrease due to the hydration process. This is because the hydration reaction will create solid hydration products, that will fill up the capillary voids. A relation in concrete science is that of the inverse relation between porosity and strength, meaning that a higher porosity will result in a lower strength. This is because the strength in concrete is delivered by the solid parts, therefore voids are detrimental to the strength [10]. The porosity is determined by the water-cement ratio and the degree of hydration, but also by the concrete mix design, the compaction and curing conditions. A higher water-cement ratio will result in a more porous concrete, which is illustrated in figure 3.16.

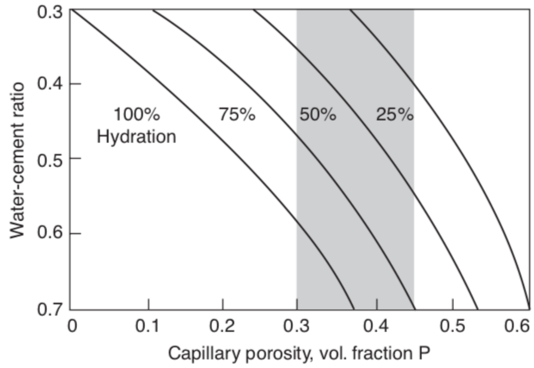


Figure 3.16: The effect of the water-cement ratio and the degree of hydration on the capillary porosity [10]

3.5.2 Permeability

The permeability is defined as the property that governs the flow rate of a fluid into a porous solid [10]. The permeability of concrete is influenced by the porosity, described in section 3.5.1, and the connectivity of these capillary pores. A high porosity will ensure easier penetration of substances at the concrete cover, but if these capillary pores are not connected, the substance will be prevented from entering further into the concrete, this is illustrated in figure 3.17.

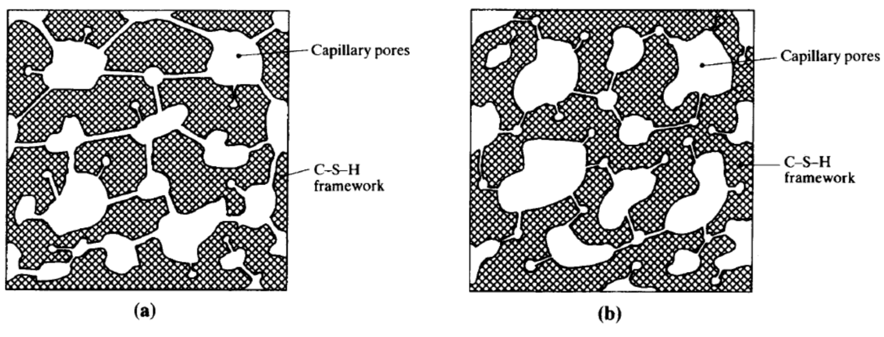


Figure 3.17: Effect of the connectivity on the permeability (a) high permeability since the capillary pores are interconnected by large passages, (b) low permeability since the capillary pores are segmented and only partly connected [10]

For a steady state flow of a fluid into a porous solid the permeability coefficient, (K), can be calculated from the expression of Darcy's law:

$$\frac{dq}{dt} = K \frac{\Delta HA}{L\mu} \tag{3.16}$$

Where dq/dt = the rate of fluid flow, μ=the viscosity of the fluid, ΔH = the pressure gradient, A = the surface area, and L = the thickness of the solid.

Age (days)	K Coefficient of permeability (cm/s x 10⁻11)
Fresh	20.000.000
5	4000
6	1000
8	400
13	50
24	10
Ultimate	6

Table 3.3: The influence of time on the coefficient of permeability

The coefficient of permeability (K) of a fresh mixed paste is between 10^-4 to 10^-5 cm/s. Since the permeability is influenced by the porosity, it is also affected by the rate of hydration. With the progress of hydration the capillary porosity will decrease, which leads to a decrease in permeability. This can be seen in table 3.3, which illustrates the permeability of a 0.7 water-cement ratio cement paste over time. Although there is a relation between the porosity and the permeability, this is not a directly proportional one [10]. This can be observed in figure 3.18, that shows that when the capillary porosity decreases from 40 to 30 %, leading to an increase in the solid/space ratio, which is the inverse of the capillary porosity, of 60 to 70 %, the permeability shows a much greater drop, around 110 x 10^{12} to 20 x 10^{12} cm/s [10].

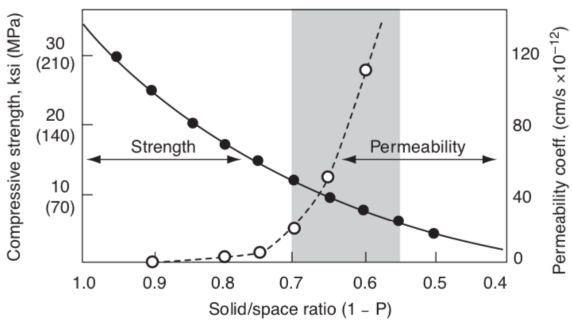


Figure 3.18: Influence of the porosity on the strength and permeability [10]

3.5.3 Water retention capacity

The capacity of concrete to absorb and hold water is called the water retention capacity. A high water retention capacity will enable concrete to stay moist for a long period of time after it has rained [29] [81]. The ability to absorb and retain water at the cover zone and inside concrete is determined by the concretes microstructure. This is influenced among others by the water-cement factor, the cement type and curing conditions. The microstructure will determine the porosity, pore structure and permeability [82]. Concrete that has a high permeability coefficient and high porosity will be able to retain an increased amount of water compared to concrete with a low porosity and permeability. This moisture retaining capacity can lead to several problems, especially in cold climates. This will be further explained in section 3.6.3 *Degradation mechanisms* on page 31.

3.6 Hardened concrete

In this section some topics concerning hardened concrete will be discussed. The sustainability and durability of concrete, and their influence on each other, as well as the degradation mechanisms will be treated.

3.6.1 Sustainability

A first definition of sustainability is given by the Brundtland Commission in 1987:

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs[83]

Economic growth should go hand in hand with environmental and social responsible decision making to guide our generation and the next ones into the future [83]. A concept for this is the 3P's of John Elkington in 1988, that states that an equal weigth should be given to the social (**p**eople), ecological (**p**lanet) and economic (**p**rofit) consequences to obtain corporate social responsibility [84].

At the moment, the construction industry accounts for 40% of energy usage world wide. This shows that in the construction industry still a lot of work needs to be done. The clinker production process, which is illustrated in figure 3.3 on page 16, releases on average a similar amount of CO_2 in the air as it produces clinker [85]. Half of this comes from the calcination process that takes place in the rotary kiln, and the other half is due to the combustion process [68]. This means that for every ton of clinker that is produced, a ton of CO_2 is released in the air. With 12 billion tons of concrete being produced yearly, it is not surprising that the clinker production process alone accounts for roughly 6% of all the man-made carbon dioxide emission in the air, and is the third largest energy consumer in the world [64] [69] [85]. Due to the growing population [30], increased economic activity and industrialization, the amount of harmful emissions released in the air keeps on increasing, even though governments and various authorities have made up incentives and legislation to regulate this [69].

Since concrete is such a commonly used building material, changing this harmful production process and reducing the emission and energy being used is high on the agenda. Therefore, alternative binders are being used more commonly nowadays, as is described in section 3.2.1 *Alternative binders* on page 16. These alternative binders are often waste products of other industries, such as fly ash, blast furnace slag and silica fume. Using these binders in the concrete mix will result in less landfill and, on paper, a lower CO_2 emission. This is because the CO_2 emissions released during production of these "waste products" can be accounted for on paper by their original industries. In the Netherlands CEM III/B is used most commonly, which has an amount of clinker of 20-34 %, the other 66-80 % consists of blast furnace slag.
Although these supplementary cementitious materials seem like a good solution, it may only be a solution of temporary nature. Producing these supplementary cementitious materials still requires harmful production processes, the only difference is that they are not accounted for on paper by the concrete industry. It seems that a long term solution is needed, in which the production of cementitious materials do not require a polluting production process.

Figure 3.19: Life cycle analysis of a product [13]

To quantify the environmental impact that a certain construction has during its life time the Life Cycle Analysis (LCA) tool is developed. In the LCA all the steps in the building process are being considered, and for each step an Environmental Cost Indicator value is added to get an insight in the total environmental costs of the product over its entire lifetime, illustrated in figure 3.19. This enables decision makers to compare several materials and their effect on the environment, to eventually choose the most sustainable building material with the lowest ECI value. In government contracts a calculation in the "Dubocalc tool" is obligatory to compare environmental costs and the sustainability of a tender.

3.6.2 Durability

The durability of a construction is the ability to maintain its minimum required performance over a certain time under influence of degradation factors [86]. The service life of a structure is defined as the period of time in which a construction is able to meet the minimum requirements of all its essential properties, under the condition that the construction is routinely maintained. In section 3.6.1 *Sustainability* on page 29 the use of a LCA tool to compare the sustainability and environmental costs of a tender application is explained. If a certain application has low environmental costs, the common thought is that it presumably scores high on sustainability. However, if the material should be replaced every 20 years while the construction is designed for a 100 years service lifetime, the actual environmental costs are a lot higher due to replacement or excessive maintenance of the building material. This means that although a construction material seems to score high on sustainability, when it is not durable and can't survive the designed service lifetime without excessive maintenance, it will actually not be the most sustainable choice. Therefor, next to the production and building process, the durability and the service life for which a construction is designed are both important parameters to be able to determine the actual sustainability. It seems that using an alternative binder instead of clinker to lower the environmental costs of the production process, discussed in section 3.6.1 *Sustainability* on page 29, might be an unsustainable choice if the durability of the concrete is affected by this replacement.

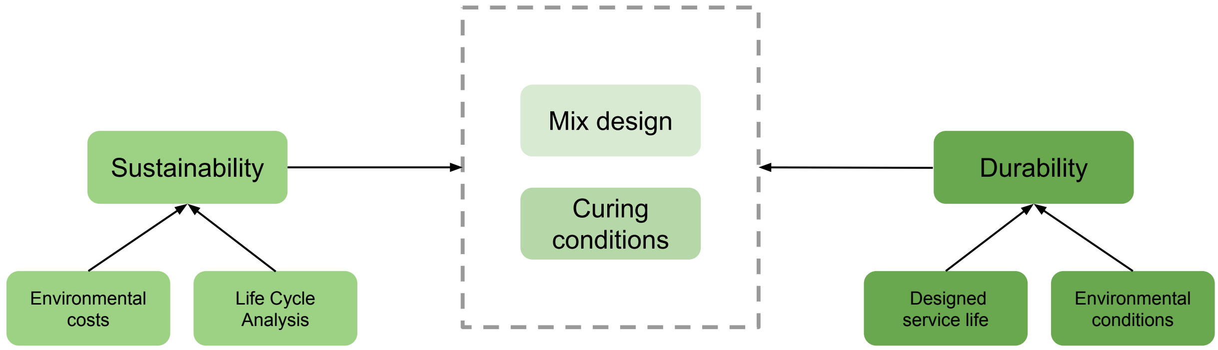


Figure 3.20: Factors to take in consideration when designing the mix design and curing conditions (*Author's figure*)

The durability of concrete

One of the most important parameters of concrete durability is the permeability, which is discussed in section 3.5.2 *Permeability* on page 27. The permeability of concrete influences the ingress of moisture and gasses with possible hazardous components for concrete, such as the ingress of CO_2 which is discussed in section 3.6.3 *Carbonation* on page 30. Concrete with a dense outer zone will make it harder for these substances to penetrate, which result in a longer service life. The permeability can be lowered by an appropriate mix design and curing conditions, which will lower the porosity and connectivity of the pores [10]. Since concrete is a heterogeneous and porous material, attention should be payed as well to the environment in which it is placed. The environmental conditions can interfere with the concrete hydration and harmful substances from the environment are able to penetrate the concrete. Therefore, an appropriate design takes into account the environmental conditions, to ensure minimal maintenance during the designed service life. In EN 206 exposure classes and their consequence for the concrete mix design are given [71]. To be able to design a concrete mix and the appropriate curing conditions several factors need to be taken into account, to be able to design a durable and sustainable construction that will perform satisfactory during its intended service life. These factors are illustrated in figure 3.20.

3.6.3 Degradation mechanisms

There are several degradation mechanisms that can attack, age, and even destroy concrete structures. Due to mechanical and structural causes, such as overloading or cyclic loading, fatigue can occur. Concrete can be physically attacked by fire or freeze-thawing, and chemically attacked by acid, sulfate or Alkali-Silica Reactions [73]. In this section some degradation mechanisms will be highlighted.

Carbonation

Carbonation is one of the main degradation mechanisms that will be focused on in this thesis. Due to the ingress of calcium dioxide (CO_2) in concrete the calcium-bearing phases, such as CH, CSH, and unreacted C_3S and C_2S, will be converted into calcium carbonate $CaCO_3^{2+}$. There are two conditions for this process to take place, namely the availability of water and CO_2. In the first steps of the carbonation process water reacts with calcium dioxide (CO_2) to form carbonate and acid, shown in formulas 3.17 and 3.18.

$$CO_2 + H_2O \longrightarrow HCO_3^- + H^+ \tag{3.17}$$

$$HCO_3^- \longrightarrow CO_3^{-2} + H^+ \tag{3.18}$$

This is followed by a reaction where the calcium-bearing phases will react with the formed acid and carbonate, creating a pH-neutralizing reaction. This is illustrated in reaction formula 3.19, where calcium hydroxide (CH) is shown as the calcium-bearing phase.

$$Ca(OH)^2 + CO_3^{-2} + H^+ \longrightarrow CaCO_3^{-2} + H_2O \tag{3.19}$$

The carbonation reaction first uses calcium hydroxide (CH), resulting in a lowering of the alkalinity of the concrete. Due to the lowered pH, the passivitation layer around the steel bars will disappear, making the steel bars more vulnerable for corrosion. [73]. Moreover when there is no more calcium hydroxide (CH) available in the pore solution, calcium silicate hydrates (CSH) will be used in the carbonation reaction. Calcium silicate hydrates (CSH) are the main building blocks of concrete. Therefore, this reaction will make the concrete weaker [64].

In formula 3.20 the carbonation depth (d) over time is given.

$$d = K \times \sqrt{t} \tag{3.20}$$

d = the penetration depth (mm), t = the time ($years$), and K = the carbonation coefficient ($mm/year$). The carbonation coefficient (K) is influenced by the alkalinity, CO_2 concentration, exposure conditions and diffusivity of the concrete [73]. The porosity has a major effect on the carbonation coefficient, as can be seen in table 3.4.

When an alternative binder is used instead of clinker, like fly ash or blast furnace slag, a lower amount of calcium hydroxide (CH) is available in the pore solution since this is already used in the pozzolanic hydration reaction of fly ash or blast furnace slag, which is explained in section 3.3.2 *Hydration of alternative binders* on page 20. Due to the lower amount of calcium hydroxide (CH) available, the carbonation reaction will start earlier with the use of calcium silicate hydrates (CSH), making the concrete more porous and permeable. Therefore blended cements with a low clinker amount are more vulnerable for carbonation and have a higher carbonation coefficient (K) [73] [64].

	Carbonation coefficient K ($mm/year$)
Concrete with a low porosity (well cured and a low w/c ratio)	2 < K < 6
A medium porous concrete	6 < K < 9
A highly porous concrete (poorly compaction and curing and a high w/c ratio)	K >9

Table 3.4: Reduction in permeability of a 0.7 water-cement ratio cement paste

Methods to prevent carbonation:
- Lowering the carbon dioxide (CO_2) concentration in the external environment.
- Creating an impermeable outer layer of the concrete to prevent carbon dioxide (CO_2) from penetrating the concrete.
- Lowering the relative humidity so there is not enough moisture present for the carbonation reaction to take place [64].

Freeze-thaw attack

During the cement hydration voids are present in the concrete, as described in section 3.3.3 *Voids in the hydrating cement paste* on page 21, and these voids can be filled with capillary water, described in section 3.3.4 *Water in the hydrating cement paste* on page 22. This can give problems when the temperature becomes lower than 0 °C, since this capillary water in the concrete will freeze, thereby expanding with 9 % in volume. When there are no empty pores available for this expansion, tensile stresses will occur inside the concrete, which can lead to cracking and spalling of the outer layers [73]. The moisture-supplying capacity of concrete, explained in section 3.5.3 *Water retention capcacity* on page 28, will highly affect the influence of the freeze-thaw attack.

Corrosion

Concrete that is reinforced with steel bars, to provide tensile strength, is vulnerable for corrosion. Corrosion is the degradation of a material due to contact with an external environment [73]. In reinforced concrete the steel can react electrochemically with the surrounding concrete. The concrete will act as a physical barrier to protect the steel from carbonation and ingress of chlorides and other harmful substances. The pore water in the concrete will act as a 'buffer' to keep the concrete pH at a high alkalinity, which leads to a passivating layer around the steel rebars [73].

There are two kinds of corrosion, carbonation induced corrosion and chloride-induced corrosion. Due to the carbonation process, which is discussed in section 3.6.3 *Carbonation* on page 30, the pH will drop and the corrosion will occur uniformly on the steel bars. Chloride-induced corrosion will locally attack the steel bars, and cause localised corrosion. Both mechanisms will cause a lowered pH. The resistance against corrosion is influenced by the cement type, the initial pH of the concrete and the buffer capacity towards alkalinity.

Penetration of harmful substances

Harmful substances can penetrate the concrete, which may lead to several kinds of degradation mechanisms.

- **Sulfate attack:** when concrete is in contact with sulphate chemical reactions occur, in which calcium hydroxide reacts with sulfate to form gypsum. This gypsum can react with calcium aluminates to form ettringite, as is discussed in section 3.3 *Concrete hydration* on page 18 [73]. Ettringite has a volume five times greater than the original hydration products. Therefor, once the concrete is hardened this reaction is detrimental for the concrete matrix [64]. A sulfate attack can be avoided by using a binder with a low content of calcium aluminates (C_3A)
- **Alkali-silica reaction (ASR):** when alkalis that exist in clinker react with water an alkali-hydroxide is formed. If reactive silica is present, which can be provided by aggregates, a reaction occurs between this reactive silica and the alkali-hydroxide, that creates an alkali-silica gel [87]. This alkali-silica gel expands in contact with moisture, which can ultimately lead to cracking [73]. ASR can be avoided by using non-reactive aggregates and limiting the alkali content of concrete. This can be achieved by using supplementary cementitious materials, such as fly ash, blast furnace slag and silica fume.
- **Acid attack**: the hydration products of concrete are in equilibrium with the pore water at a high pH, as is discussed in section 3.3 *Concrete hydration* on page 18. This equilibrium is interrupted when acid penetrates the concrete, resulting in a neutralizing reaction in which the hydration products will be dissolved and the pH of the concrete is lowered [73].

Chapter 4

Moss concrete

The greening of outside walls and roofs of buildings and structures will contribute to a sustainable and livable city design, called "The Green Compact City", as is explained in chapter 2 *Sustainable cities* on page 10. Concrete can be used as a means to grow mosses, thereby enabling more green in dense urban areas that satisfy the space saving requirement posed by 'the compact city' design. In this chapter the concrete knowledge obtained from chapter 3 *Concrete* will be used to explore the possibilities of moss growth on concrete. In the first section the need for moss growth on concrete is emphasised, followed by the explanation of the formation of mosses on concrete. In the third section the influencing factors that will determine moss growth on concrete are discussed. Finally, some of the drawbacks of moss growth on concrete will be stated in the last section.

4.1 Why moss concrete?

The advantages of moss concrete over several other greening methods, such as living wall systems or rooted systems, is that moss concrete needs little maintenance, and if used correctly, will be cheap and efficient. The low weight of the mosses and the absence of roots will enable the use on existing buildings and structures without re-evaluating the structures capacity. This in comparison to several prefabricated roof and wall panels, that can soak up a lot of water which might lead to exceeding the load capacity. As is explained in chapter 2 *Sustainable cities* on page 7 the use of green in urban areas has several advantages, such as lowering the urban heat island, providing ecosystem services and providing insulation properties. More specific properties of moss concrete will be investigated in this section.

Figure 4.1: A natural air filter [14]

Air filters - physical health

In the past 40 years moss species such as the *Tortula Muralis* have been used to monitor pollution in the air [88]. This is because mosses have a high accumulation ability to absorb dissolved substances, based on their ion - exchange properties. Due to the high surface to mass ratio mosses can effectively act as air filters for airborne particulates that carry atmospheric pollutants, and fine dust particles carried by the wind [89]. These small dust particles come from among others the industry, traffic, and private households, and can cause several health problems. The finer the dust particle, the deeper it can penetrate into the lungs, causing troubles for the respiratory system [90]. The nasal and pharyngeal cavities are unable to filter particles that have a diameter smaller than 10 μm, resulting in the accumulation of ultra fine particles in the alveoli of the lungs [91]. Mosses absorb atmospheric water, such as rain and dew, and the nutrients dissolved in them via their surface [91]. Particulate matter is a type of dust that will not sink due to its size that is smaller than 10 μm, and can only be precipitated by wet deposition. If this floating particulate matter is brought in contact with moss, it will be kept mechanically between the moss leaflets. The surface area enlargement of moss plants is almost thirthy-fold, achieved by the closely arranged leaflets. This makes mosses very suitable for air filtering in comparison to artificial surfaces

[91]. Research found that an increase of green will lead to a better air quality, that subsequently will lead to a lowering of respiratory problems, visualised in table 4.1[90].

Respiratory disorder	10 % green space	90 % green space	Percentage decrease
Upper respiratory tract infection	84	68	19,1 %
Bronchitis	16	14.7	8,1%
Asthma, COPD	26	20	23,1%

Table 4.1: The prevalence rate of several respiratory disorders per 1000 inhabitants, with 10% and 90 % of green within 1 kilometer from their home.

Acoustics

Due to urbanization, globalisation, and increased mobilization, the noise levels due to transport have increased in the past decades. The World Health Organization has recognised this community noise, that includes transport noise, as a public health issue and has done research to come up with guidelines to address this [92]. In these guidelines the threshold values for noise levels are set at $55\ dB$ during daytime and $30\ dB$ at night, above which a significant impact on human well being is expected [93]. Research found that throughout Europe, more than 44% of the population is exposed to sound levels higher than 55 dB coming from road traffic near their house [94]. A conservative estimate of the social costs of traffic noise amount to at least €40 billion annually [93]. Although several solutions have been implemented to reduce this noise, such as new types of top layers on the road, more silent engines for traffic, and improved tire engineering, at limited distance from roads the sound levels are often still too high [94]. The implementation of green facades can lead to improved sound insulation, thereby reducing the noise levels. However, only insulating facades with vegetation will not give the wanted results, since people should be able to open a window for fresh air, which will diminish the effects of the green facade [95]. Therefore, the green facade should be complemented with a green roof to obtain the needed sound reduction [96]. Research found that the type of roof or facade and their green coverage are important parameters for the acoustical quality of a house [97]. A lowering of $5\ dB$ could be reached by applying flat extensive green roofs and of $8\ dB$ in a street canyon configuration with a 45 °saddle-back roof [94]. However, quantifying the noise level reduction is extremely dependent on the specific situation at the measuring points, and strongly depends on the geometrical details and setting of the building, and the characteristics of the local traffic. An estimate of the noise reduction of flat green roofs is typically $3\ dB$ for vehicle speeds between $30\ km/h$ and $70\ km/h$ [96]. This is comparable to halving the intensity of the traffic on the road (for example from 10.000 to 5.000 vehicles daily), or halving the maximum speed (up to a 90 km/h), and is equal to a reduction of half of the power of the noise intensity [98]. Moss concrete can also be used inside, to lower the noise level and ensure the wanted acoustic behaviour. This concept is already seen in practice, as is illustrated in figure 4.2.

Figure 4.2: Acoustic moss wall [15]

CO_2 uptake

In chapter 3 *Concrete* on page 29 the role of the cement industry on the annual carbon dioxide ($CO2$) production is discussed. Manufacturing cement accounts for 6 % of the global $CO2$ emissions worldwide. To mitigate this effect mosses can be grown on concrete, because mosses take up $CO2$ and use it to produce biomass. The CO_2 fixing rate of the moss species *Tortula muralis* is measured to be 2.2 μmol per gram dry weight per hour [99]. In part III *Case study* on page 85, this value is used in several case studies to get insight in the ability of moss concrete to fixate CO_2.

Cooling and insulating properties

As is explained in chapter 2 *Sustainable cities* on page 7, the Urban Heat Island effect can be reduced by incorporating more greenery into the urban build environment. This greenery will act as a water reservoir and increase the transpiration of vegetation, leading to a reduced temperature [100]. The water retention capacity of mosses is high, especially in combination with porous and permeable concrete, which will result in a reduction of the UHI effect. Moreover, the albedo of the facade or roof will probably be higher when moss concrete is being used, leading to more reflected sunlight instead of absorbed and transformed into heat, as is explained in chapter 2 2 *Sustainable cities* on page 8. Research found that by greening 30% of the urban surface, already 2/3 of the total cooling properties will be reached, visualised in figure 4.3 [101].

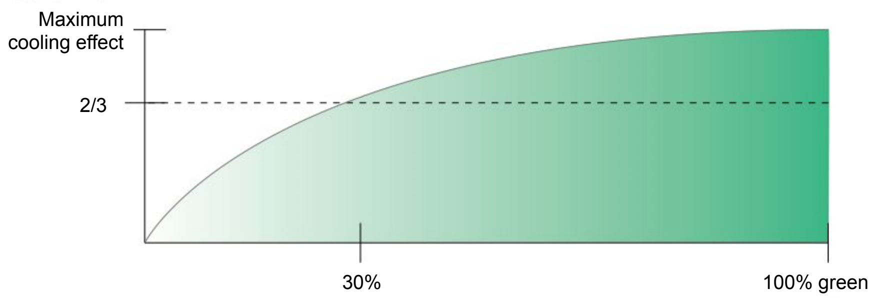


Figure 4.3: The maximum cooling effect [16] *(Altered by author)*

Aesthetics - Mental and physical health

Moss concrete will contribute to the aesthetics of thr surrounding area. Due to the transformation of a facade of plain concrete into moss concrete, the overall amount of green area will increase. This will make the environment more attractive for outside engagement and promotes walking and cycling [90]. Research found that there is a correlation between the exposure to natural places, such as the view from a window or being within natural places, and a positive mental health [102]. When regularly engaging in nature a decreased risk of mental disorders is achieved. Thereby, this will lead to a lowering of stress levels, which will subsequently lead to a lowering of multiple health risks that are assigned to stress [16] [103]. Health levels are more strongly correlated to the availability and amount of green area than to the degree of urbanization [104]. A correlation has also been found between the number of doctor visits in a certain area and the amount of green space available in that area [105]. A decline of 0.8 visits per 1000 inhabitants is reached for an increase of 1% in green area [105]. The access to local green space is important for the quality of life and for the sustainability and livability of cities, as is explained in chapter 2 *Sustainable cities* on page 7 [105][106] . The advantages of having more greenery in cities goes even so far that due to the predicted positive health outcomes, improved ecological knowledge, and influence on behavioral choices, the result of more greenery in cities would actually be overall cost saving [107][102] .

	10 % green space	90 % green space	Percentage decrease
Mental disorder			
Depression	32	24	25 %
Anxiety disorder	26	18	30,8%
Physical Effects			
High blood pressure	23,8	22,4	5,9%
Cardiac disease	4.7	4	14,9%

Table 4.2: The prevalence rate of several mental disorders per 1000 inhabitants, with 10% and 90 % of green within 1 kilometer from their home.

Biodiversity

Our Earth is unique because of its ability to support life, and the most extraordinary feature of life on Earth is the diversity [108]. Around 9 million types of animals, plants, bacteria, protists and fungi inhabit our planet Earth, together with 7 billion people [108]. The advantage that all these different species have given to support and maintain life is only now seen properly, since it is in endangered by human activity. The term biodiversity refers to the number of different genes, species, organisms, and communities ranging from a small ecosystem to the global biosphere [109]. Due to the human activity of the past decades, the population growth and increased consumption, a decline in the number and variety of species is found, resulting in a loss of biodiversity [109]. This biodiversity loss leads to multiple detrimental effects, such as a reduced productivity of an ecosystem (the amount of food converted into biomass), a lowering of the quality of the ecosystem services, and an altering in the structure and proper functioning of an ecosystem [109]. One of the main reasons that causes this decline in biodiversity is the loss of habitat. Having an abundant of green area in cities will simultaneously result in more biodiversity. With moss grown on facades and roofs, new habitats can be created for multiple species of animals and plants. This will result in the development of new ecosystems, that will subsequently contribute to the provision of ecosystem services, as is described in chapter 2 *Sustainable cities* on page 9.

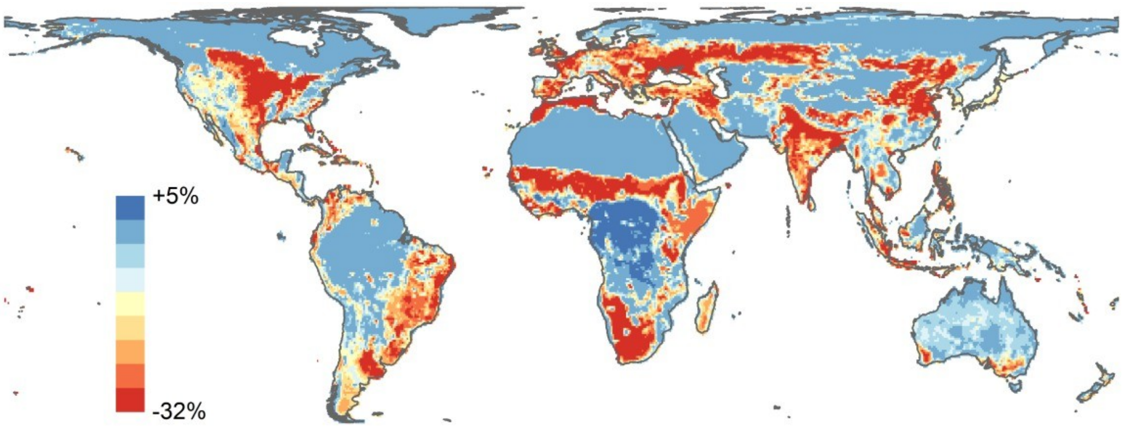


Figure 4.4: The biodiversity gain and loss globally [17]

Urban flooding

Due to the loss of green space in a city and the conversion of natural land into urbanized land, the surface of a city has changed, explained in chapter 2 *Sustainable cities* on page 7. This change has led to less permeable and porous surfaces that can absorb rain. This, in combination with a limited urban sewer system, causes problems when heavy rainfall occurs. Since the expectation is that the Netherlands will endure more heavy rainfall in the upcoming decades, solving this problem is high on the agenda [110]. This urban flooding can be mitigated or even prevented when more vegetation is applied in urban areas [111]. Vegetation can lead to a decrease in water runoff during a storm by interception, retention, and the evaporation of rainwater [112]. Moss concrete has the potential to enable this, since the water uptake of moss is very high. The exact water uptake of two moss species will be measured with experiments and calculated for eleven case studies in part III *Case study* on page 85.

4.2 The formation of mosses on concrete

The process that enables mosses to grow on concrete will be explained in this section. Concrete can serve as a living habitat for several organisms, that will contribute to the growth of mosses on concrete [81]. There are several phases that concrete will go through to form mosses on concrete. In figure 4.5 these phases are illustrated according to Sparrius (2016) [81]. Each phase will be treated separately in this section.

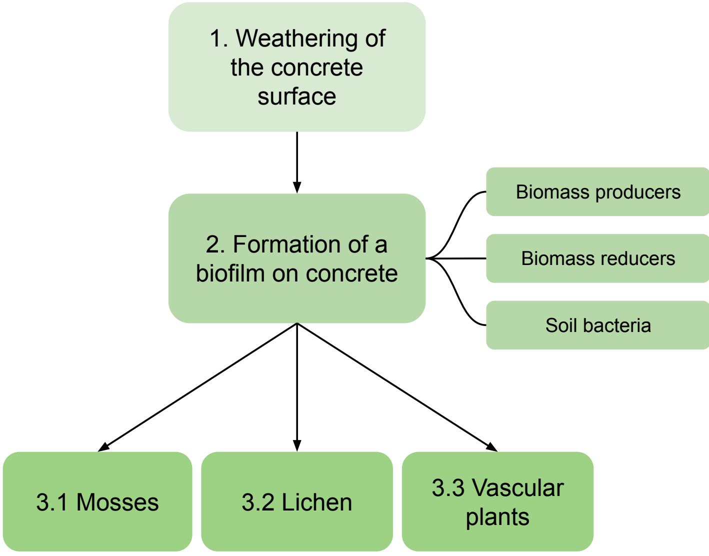


Figure 4.5: Growth process at the concrete surface *(Author's figure)*

1. Weathering of the concrete surface

The process will start when the concrete surface is weathered, meaning that the alkalinity of the concrete at the surface is a bit lowered and the concrete is roughened. This can occur due to climate influences, such as freeze-thaw cycles or due to chemical substances that have penetrated the concrete, both discussed in section 3.6.3. *Degradation mechanisms* on page 30. Even if this affected upper layer of the weathered concrete is only a millimeter thick, micro-organisms will be able to settle on the surface layer [81].

2. The formation of a biofilm on the concrete surface

A biofilm is a layer of micro-organisms that settle on the weathered concrete. These organisms can settle into the pores on the surface of the concrete, or via a mucous layer that they produce themselves. The growth of the biofilm is influenced and stimulated by several factors, and can be captured in four steps, as is illustrated in figure 4.6 [80]. The first step that is identified is the initial colonization of micro-organisms on the concrete surface. This colonization can be the result of deposition by rainwater, wind, and runoff, or due to physical contact of concrete with soil, vegetation, animals or animal feces. The second step in this process is the existence of an hospitable concrete surface. The concrete surface should have a sufficiently lowered pH, caused by the process illustrated in figure 4.7, a suitable concrete microstructure and enough surface roughness. The third step that allows micro-organisms to grow into a biofilm is the availability of energy sources. The metabolic processes carried out by the micro-organisms need water, nutrients and minerals. When all of these steps have been successful, the growth and reproduction of the micro-organisms can occur [80]. In a biofilm the following micro-organisms are found [113]:

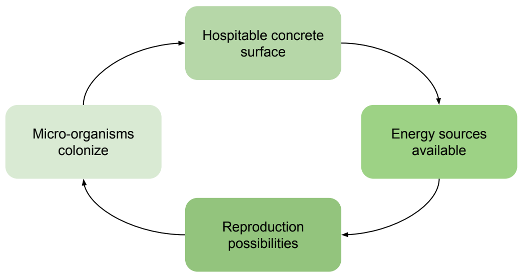


Figure 4.6: The biological growing process *(Author's figure)*

Biomass producers
This are autotrophic organisms, meaning that they are able to synthesize their own food from organic mass. Biomass producers can be single cell organisms and filamentous green algae, such as Chlorophyta and Chlorococcum, or cyanobacteria, such as Nostoc and Gloecapsa [81]. Cyanobacteria are the only micro-organisms discovered that are able to fix atmospheric carbon while utilizing sunlight as an energy source [80]. These organisms do not consume other organisms, but are consumed by heterotrophic organisms.

Reducers
These organisms break down complex organic connections in an oxidation reaction. Reducers can be bacteria and moulds, and can break down organic material that has landed on the concrete surface, such as soil and fallen leaves.

Soil bacteria
These soil bacteria will break down the anorganic degradation products of the Reducers even further through an oxidation reaction. Examples of soil bacteria that can be found on the concrete surface are ammonium oxidizing bacteria, such as Nitrosomonas and Nitrospira, iron and manganese oxidizing bacteria, and Nitrite oxidizing bacteria, such as Nitrobacter and Nitrococcus.

The micro-organisms that make up the biofilm excrete acid and CO_2, that lower the pH of the concrete surface. Due to this pH drop the concrete surface will be a more hospitable environment for micro-organisms to settle on, and will lead to the growth of the biofilm [81]. This self-reinforcing process can be found in figure 4.7. Due to the pH drop several degradation mechanisms in concrete can occur, such as corrosion of the reinforcing bars which is discussed in section 3.6.3 *Degradation mechanisms* on page 30.

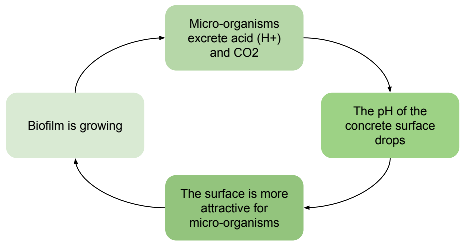


Figure 4.7: The self-reinforcing process of the formation and growing of a biofilm *(Author's figure)*

3. Growing of vegetation on the surface of concrete

The formed biofilm can develop into vegetation on concrete, such as mosses, lichens and vascular plants. The type of vegetation and speed with which it will develop is influenced by the pH, the environmental conditions, and the roughness of the surface [81].

Figure 4.8: A pioneer moss *(Author's figure)*

Mosses
The biofilm can serve as a culture medium which, together with the weathered concrete surface, enables mosses to grow. These primitive plants have stems and leaves and root-like sutures called rhizoids, that will settle into pores and cracks on the surface of concrete. Mosses prefer humid, half sheltered places to settle on, because the fertilization occurs due to the swimming of male cells to the female plants [81]. Therefore, horizontal areas that are periodically covered with moisture provide optimal environmental conditions for mosses. The concrete should be porous with isolated cracks, and have a high water retention capacity to provide the roots of the mosses with enough water.

Mosses can become 0,5 - 1 *cm* thick and will grow and produce biomass at the top, which will be broken down and decayed at the bottom by bacteria and moulds. The bottom of the moss cushion should be kept moist at all times to enable this process. While the production and decaying process of biomass continues, acid will be excreted to the underlying concrete [81].

There are two forms in which mosses can grow, as separate cushions or as a mat. The first moss pioneers that grow on concrete will grow in separate cushions, visualised in figure 4.8. After a couple of years of moss growth on concrete the moss form is different. The mosses now have formed a solid moss mat on the concrete. When this moss form is found earlier it is often due to the colonization of vegetation surrounding the concrete [81].

Lichens

A symbiosis of a funghi and a cyanobacteria or algae together form lichens. Organic content is provided by the algae or cyanobacteria to the fungi via photosynthesis. Inorganic compounds, shelter and anchorage is provided by the fungal species to the algae or cyanobacteria [80]. Due to the developed biofilm, carbonation and weathering of the surface the pH is lowered, from 14 to 10, which enables lichens to settle on the biofilm. Nutrients are provided by rainwater and degradation products in the biofilm, such as ammonium and phosphate. These nutrients, together with an elevated water retention capacity, will enable lichens to grow. In contrary to mosses, lichens prefer sunlight and dry places and will penetrate at most 0,1 *mm* into the concrete [81]. The lichens grow slowly because of their short physiological active period. In the Netherlands 700 types of lichens can be found, from which 10 types are found on weathered concrete surfaces [81]. The environmental conditions will determine the type of lichen that will settle on the concrete and the surface that they will cover. The most common types of lichens that are found aren't striking and are black, grey or yellow [81]. The more striking lichens that can be found on the concrete surface are often powdered or leaf-shaped species.

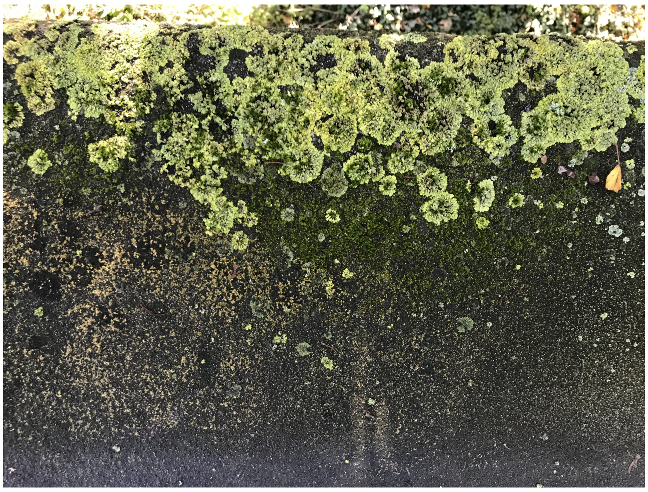


Figure 4.9: Lichens *(Author's figure)*

Vascular plants

Even plants are able to grow on the concrete surface, although this is usually the result of the surrounding vegetation. Horizontal surfaces are able to facilitate the growing of sod-forming succulents. Deep crevices in the concrete enable the roots of grasses, bushes and even trees to grow independently. Moss cushions on the concrete surface promote the formation of vascular plants because they retain water, thereby providing the roots of the vascular plants with enough moisture [81].

Figure 4.10: A vascular plant [18]

4.3 Influencing factors

Several factors determine the presence and type of biofilm that will colonize on the surface of concrete and the vegetation type that this biofilm might grow into. In figure 4.6 the steps are illustrated that will allow micro-organisms to colonize, settle and grow. In this section the effect of each of these steps (colonization possibilities, hospitable concrete surface and growing factors) on the biofilm growth is discussed. The role of the climate on the growth process is also taken into account, illustrated in figure 4.11.

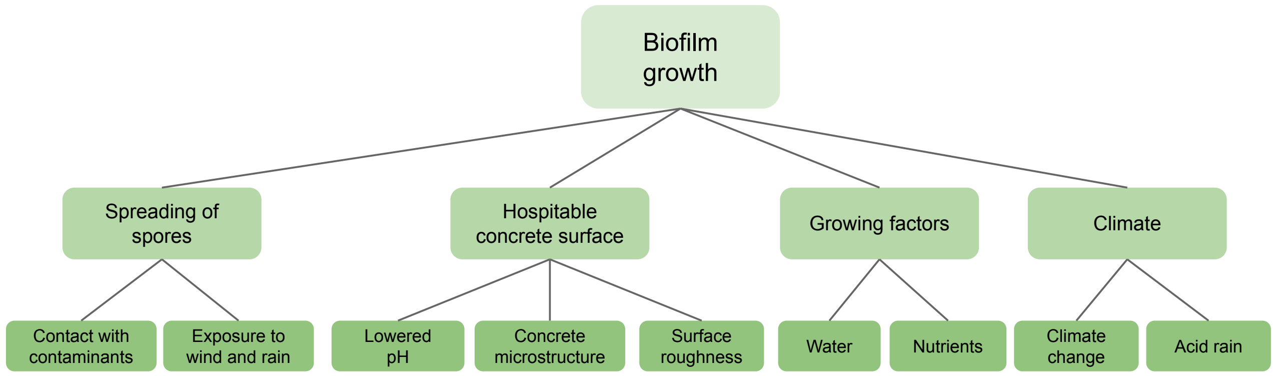


Figure 4.11: Influencing factors on the formation of a biofilm on the concrete surface *(Author's figure)*

Colonization possibilities

The process of microbiological growth starts with initial colonization on the concrete surface [80], because a plain concrete surface has little to none organisms living from oneself. These micro-organisms should be provided by another source, such as exposure to rainwater or runoff, or by organic material transported through the wind. Another way could be through physical contact with contaminants, such as animals, plants and soil [80]. All of these sources could lead to the deposition on the surface of concrete and initiate the microbiological growing process.

Hospitable concrete surface

When examining the surface of concrete, it is surprising that a biofilm is able to grow on it considering the few advantageous characteristics to stimulate and support biofilm growth. However, nature certainly seems to find a way. There are several factors of the concrete surface that influence the biofilm growth, namely the surface roughness, pH, and concrete micro-structure.

I. Surface roughness
A rough surface enables retention of moisture, nutrients and organic material [81]. This is needed for the colonization and growing of the micro-organisms that have settled on the surface. Secondly a rough surface will provide attachment points for micro-organisms, such as fungal spores and bacteria. These attachment points provide the micro-organisms with shelter, and enable them to settle on the concrete surface. Multiple experiments have been executed to confirm this positive influence of the surface roughness on moss growth [114].

II. pH
Due to the degradation mechanism carbonation, explained in section 3.6.3 *Carbonation* on page 30, the pH of concrete decreases. Young concrete has a high surface pH, usually around 12-13, because the first millimeters of the concrete have not yet been carbonated. This results in an environment that is not suitable for most micro organisms, because the high alkalinity causes bio-energetic problems. Therefor, the majority of organisms grow between a pH of 2 - 9 [80]. However, there are some species that are able to survive under these hostile circumstances, and will cause the pH to lower by a self-reinforcing process, as is illustrated in figure 4.7. This self-reinforcing process together with carbonation will result in a pH of 8-9 at the first millimeters from the surface. A wider range of micro-organisms can withstand this less alkaline environment and are able to colonize and grow on the concrete surface [80].

III. Micro-structure
The microstructure of concrete will determine several concrete properties, such as the porosity, permeability and pore connectivity, as explained in section 3.5 *Concrete properties* on page 26 [64]. Research has found that these properties of concrete have a significant effect on the biofilm growth [80]. The concrete microstructure and its corresponding

properties determine for example the water retaining capacity, as is explained in section 3.5.3. A high water retaining capacity will create an optimum environment for micro-organisms and vegetation to settle on, because it will provide moisture for a longer period of time after it has been raining [82]. This high water retaining capacity is created when concrete has a high porosity, a high permeability and an open pore structure [82]. These properties can be obtained by appropriate mix design and curing conditions, as illustrated in figure 3.15 on page 26.

Growing factors

The available growing factors will determine the speed of the biofilm growth. A surplus of moisture is necessary, which can come from different sources, such as rainfall or a runoff pattern on the concrete. Nutrients should be available to serve as energy source to expand the biofilm. On a plain concrete surface little nutrients will be available, therefore even the smallest amount of nutrients will contribute to the growth of the biofilm. These nutrients can be provided by rainwater, air pollution, animal feces and even by applied coatings on the concrete, such as curing compounds and form release oils [29]. Besides moisture and nutrients present, the environment will have a great influence on the growing speed of organisms. The ideal environment to enable the biofilm growth will be somewhere with enough moisture and light present, but not too much direct sunlight. Therefore, the biofilm growth will be minimal to none in sheltered places [82].

Climate

The climate in which concrete is situated will greatly influence the type and growing speed of the biofilm. Over the last decades the staining on concrete due to biological activity has increased [80]. Research found that this increase can be allocated among others to climate change and a decrease in acid rain [82].

I. Climate change

The climate is changing due to human action. In the Netherlands the overall ambient temperature has increased. Measurements executed from 1906 until 2017 showed an average ambient temperature increase of 1,9 $^{\circ}C$ since 1906 [115]. In the past 30 years a yearly temperature increase of 0,04 $^{\circ}C$ has been found [115]. This results in milder winters with less extremes, illustrated in figure 4.12 that shows the yearly number of days in which the temperature is 0,0 $^{\circ}C$ or lower [19]. Moreovern, climate change has caused an increase in precipitation in the Netherlands. The KNMI found that the overall amount of precipitation has been increasing from 690 mm to 874 mm in the period from 1910-2017 in the Netherlands, an increase of 27 % in 108 years, illustrated in figure 4.13 [20]. The elevated temperature and increased precipitation extend the period in which the biofilm is active.

II. Acid rain

The pH of precipitation in the beginning of the eighties was between 4,0 - 4,5, due to air pollution [116]. The harmful gasses emitted by traffic, agriculture and the industry contained nitrogen and sulfur, that ended up on the ground due to precipitation. This had detrimental effects for the soil, groundwater and the biodiversity [117]. Organisms disappeared from rivers and lakes, and trees and vegetation died. Stricter policies on the emission of (harmful) gasses containing sulfur and nitrogen in the past decades have worked. The lowering of emitted gasses has led to an improvement in the quality of rainwater, leading to a pH of precipitation in 2008 5,0 - 5,5 [116] [117]. This increased pH seems to have a positive influence on the growth process of mosses, lichens and vegetation.

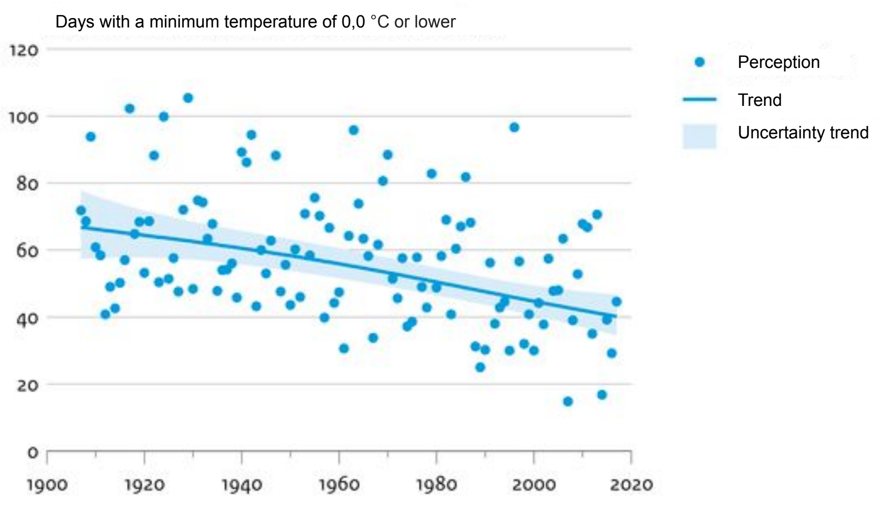


Figure 4.12: Number of days with a mimimum temperature of 0.0 °C or lower [19] *(Altered by author)*

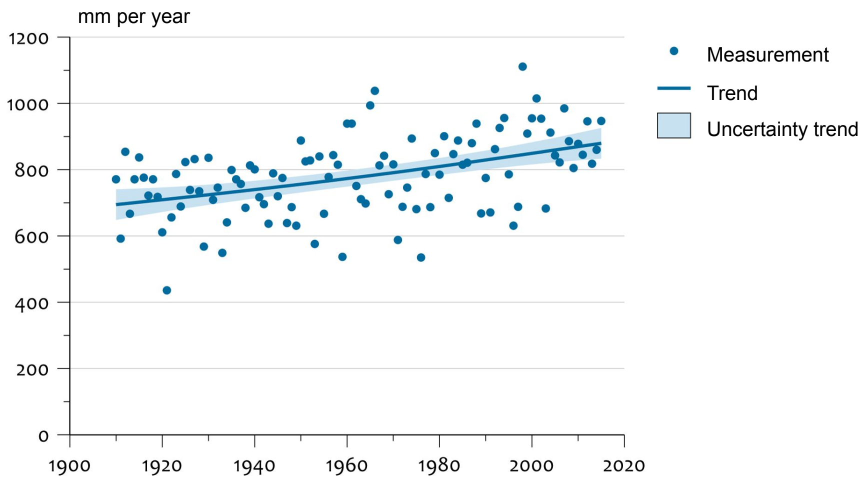


Figure 4.13: Yearly amount of precipitation in the Netherlands between 1910-2017 [20] *(Altered by author)*

4.4 Drawbacks

Although it might seem that the advantages for moss concrete are endless, this research would not be complete without giving the drawbacks of moss growth on concrete. Foremost, the first drawback is that porous and permeable concrete, which is needed for mosses to be able to grow, will be vulnerable for several degradation mechanisms. This is explained in chapter 3 *Concrete* on page 30. Therefore, the question arises if concrete with abundant moss growth on it is sufficient to be used as a construction material. Although further research should be done to investigate this, several solutions can be found to overcome this, which will be discussed in part III *Case study* on page 96.

The second drawback is concerns the moss growth process. At this moment it is unknown at exactly which locations mosses will grow. Thereby it has not yet been found how long it takes mosses to grow into a solid moss mat once the first pioneer moss cushions have settled. Further research should be executed to enable more knowledge about the speed and certainty of moss growth at different locations.

Part II

Experimental program and results

Chapter 5

Hypothesis formation

The aim of this research is to understand the unintentional formation of moss growth on concrete, to eventually be able to design moss concrete. In chapter 4 *Moss concrete* on page 33 the formation of mosses on concrete and the influencing factors are explained. It seems that a biofilm growth on concrete will occur under several conditions, illustrated in figure 4.11 on page 40. This biofilm can subsequently grow into moss, as illustrated in figure 4.5 on page 37.

Although it is known that there are multiple environmental influencing factors that will determine the presence or absence of moss growth on concrete, explained in section 4.3 *Influencing factors* on page 40, this research will focus solely on concrete influencing factors. It can be seen in figure 5.1 that a hospitable concrete surface is needed for the biofilm growth, which enables mosses to settle. This hospitable concrete surface is provided by the concrete microstructure, a lowered pH, and a sufficient surface roughness. The aim of this research is to find how this hospitable concrete surface unconsciously is created in practice.

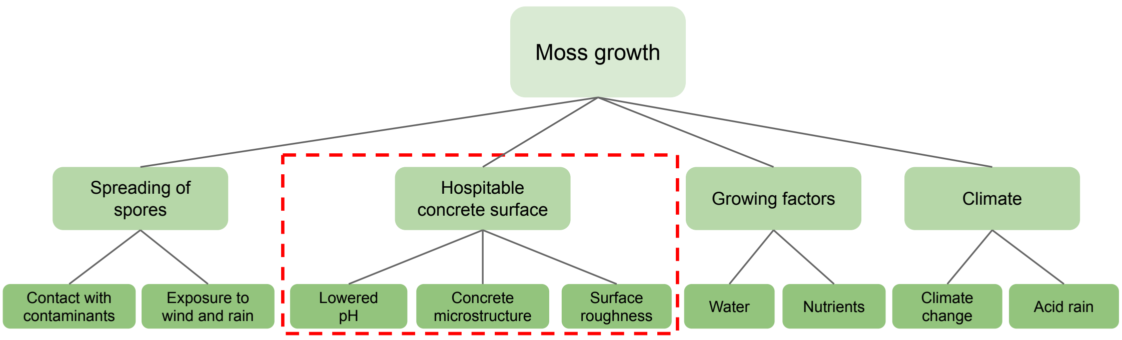


Figure 5.1: Influencing factors on the formation of a biofilm *(Author's figure)*

1. Insufficient curing
In research executed to investigate possible causes and effects of unwanted and spontaneous moss growth on concrete, it has been found that the porosity and permeability of the cover zone of concrete plays a dominant role [29]. The presence of moss growth on concrete is positively related to the concrete properties porosity and permeability, explained in section 3.5 *Concrete properties* on page 26 [21]. It seems that a porous and permeable concrete cover zone will deliver the needed microstructure and surface roughness, that will among others enable mosses to settle and provide them with moisture, as is explained in section 4.3 *Influencing factors* on page 40.

Accidentally obtaining concrete with a cover zone that is highly porous and permeable is unwanted and can be labelled as imperfect concrete [62]. This is because a highly porous and permeable cover zone weakens the concrete by making it vulnerable for several degradation mechanisms, as is explained in section 3.6.3 *Degradation mechanisms* on page 30 [66]. The causes of this porous and permeable concrete cover zone must first be understood, to eventually be able to consciously repeat this process to obtain moss concrete. On the other hand, when these causes are known, the unwanted abundant moss growth that occurs nowadays in practice can be ceased.

A cause that can be found that is likely to be attributed to this highly permeable cover zone, although not fully understood, is the insufficient curing after casting of concrete, especially of concrete with a low-clinker content [29] [118]. Research has already found that the curing conditions have a major influence on the durability parameters of concrete, such as the porosity and permeability [118]. It seems that during standard testing, which is after 28 days under water- or fog room curing, a low-clinker content concrete shows no signs of an imperfect cover zone, and actually performs sufficient when the strength and durability performance is considered. However, under real in situ casting conditions the performance often fails to meet the potential of these concretes, especially the durability parameters turn out to be much worse than what would have been expected based on the laboratory testing [119]. This shows that there is a gap between the knowledge obtained from literature and laboratory testing, and what actually happens in practice. Thereby there seems to be relatively little know-how on the different effects of widely used curing technologies on the bulk material of concrete compared to the effects for the cover zone concrete [118]. This is also shown in the fact that structures are encountered where early on repair is needed, even though the codes have been followed, which implies that the service life should be at least 50 years [119].

To investigate the effect of the curing conditions and the low-clinker content on concrete, together and independently of each other, and their influence on the porosity and permeability of the concrete cover zone, the following hypothesis has been formed and will be tested:

- *A low-clinker content concrete (CEM III/B based) is more vulnerable for insufficient curing (no curing or paraffin curing) than concrete with a high-clinker content (CEM I), leading to a relatively more porous and permeable concrete cover zone.*

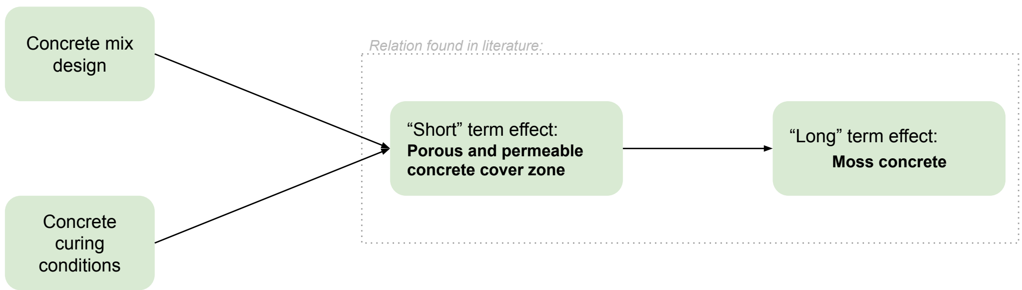


Figure 5.2: Hypothesis 1 *(Author's figure)*

2. Buffering capacity
The buffer capacity towards alkalinity of a certain concrete mix can be explained as the ability to neutralize incoming acid without compromising on the alkalinity of the pore solution. In other words, the amount of acid that a certain concrete can neutralize without lowering its internal pH. When concrete has a low buffer capacity towards alkalinity, the durability is in jeopardy. This is due to a higher risk of corrosion and less autogeneous self healing, which is explained in section 3.6.3 *Degradation mechanisms* on page 30. Another effect that is seen with a low buffer capacity is that of an increased risk of carbonation. In low buffer capacity mixes, the pore solution has a lower amount of calcium hydroxide (CH) available. Therefore, calcium silicate hydrates (CSH) will be used during carbonation, which results in more porous and permeable concrete, this effect is explained in section 3.6.3 *Carbonation* on page 30.

As is illustrated in figure 5.1, a condition that will allow a biofilm to grow, and eventually mosses to form, is a lowering of the pH of concrete, especially at the cover zone. This influencing factor is explained in section 4.3 *Influencing factors* on page 40. The micro-organisms that make up the biofilm excrete acid and CO_2, which lowers the pH of the cover zone of the concrete. This self-reinforcing process is illustrated in figure 5.3. Therefore, a concrete with a low buffer capacity towards alkalinity is more bioreceptive.

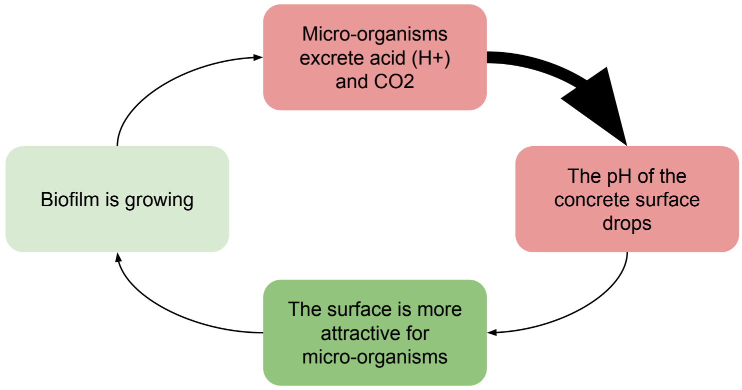


Figure 5.3: The effect of acid on the pH *(Author's figure)*

It is known that concrete mixes that contain a high percentage of alternative binders, such as fly ash or blast furnace slag, will have a less alkaline pore solution compared to mixes with a high-clinker content. This is due to the hydration process of these alternative binders, which uses calcium hydroxide, a phenomenon that is explained in section 3.3.2 *Hydration of alternative binders* on page 20. However, the effect that the clinker content has on the buffer capacity, is unknown. To test the buffering capacity towards alkalinity of various mixes that differ in clinker content, the following hypothesis is formed:

- *A low-clinker content concrete (CEM III/B based) will have a lower buffering capacity towards alkalinity than concrete with a higher clinker content (CEM I). A low buffer capacity leads to a lowering of the durability, since there will be more corrosion, the carbonation will lead to more porosity, and the concrete will be more bioreceptive.*

In chapter 6 *Experimental program* the experiments that have been executed to test these hypothesises will be explained.

Chapter 6

Experimental program

The hypothesises that have been formed in the chapter 5 *Hypothesis formation* will be tested and quantified using experiments. In this chapter the experimental approach used in this research is explained, and the experiments that are conducted are elaborated. The method and expected results of each experiment will be discussed.

6.1 Approach

The knowledge from the literature study, which consists of chapter 2 *Sustainable cities*, chapter 3 *Concrete* and chapter 4 *Moss concrete*, combined with the formed hypothesises from chapter 5 *Hypothesis formation* are the starting point of this experimental program. Mortar samples have been produced in the laboratory of SGS Intron to serve as test material during the experiments. The choice for mortar samples instead of concrete samples has been made to exclude the effect of aggregates during the experiments. The produced specimens differ in binder type and curing condition, which gives a total of nine combinations. In section 6.2 *Mortar specimens* on page 51, the choice of constitution of the specimens and curing methods are explained.

Multiple experiments will be executed to receive data from which meaningful conclusions can be drawn that will confirm or reject the formed hypothesises from chapter 5 *Hypothesis formation*. A choice has been made to test the specimens on durability parameters (water absorption, drying behaviour, buffer capacity) instead of strength testing. This is because research has shown that the durability parameters have a greater sensitivity to curing [120]. The strength of a specimen is to a large extend a property of the major "bulk"of a certain concrete sample, while the actual durability performance is influenced by the processes and microstructure of the cover zone of the concrete [118]. Strength testing is therefore, not sufficiently sensitive enough to monitor this durability performance of the outer layer when different curing methods has been used, and therefore durability performance testing is more effective to visualise the effects of "insufficient" curing [118][121].

The experimental program is illustrated in figure 6.1 on page 50. Each experiment will be executed on specimens that differ in binder type and curing conditions. The specimens will be manufactured in double or in threefold, to be able to draw accurate conclusions from the obtained data of the experiments.

Hypothesis 1: *A low-clinker content concrete (CEM III/B based) is more vulnerable for insufficient curing (air curing or paraffin curing) than concrete with a high-clinker content (CEM I), leading to a relatively more porous and permeable concrete cover zone.*
To test the first hypothesis, specimens that differ in clinker content and curing conditions are created and used for several experiments. The intention of the experiments is to gain more insight in the effect of the curing conditions and binder types on the porosity and permeability of the concrete cover zone. This is achieved with a water absorption and drying test, an epoxy impregnation, a carbonation test and Mercury Intrusion Porosimetry.

Hypothesis 2: *A low-clinker content concrete (CEM III/B based) will have a lower buffering capacity towards alkalinity than concrete with a higher clinker content (CEM I). A low buffer capacity leads to a lowering of the durability, since there will be more corrosion, the carbonation will lead to more porosity, and the concrete will be more bioreceptive.*
The second hypothesis will be tested with visual observations and a buffer capacity test, in which the buffer capacity towards alkalinity will be tested. Specimens that differ in clinker content and curing conditions are created and tested.

This will give insight in the influence of the clinker content and curing conditions on the buffering capacity towards alkalinity and on the bioreceptivity.

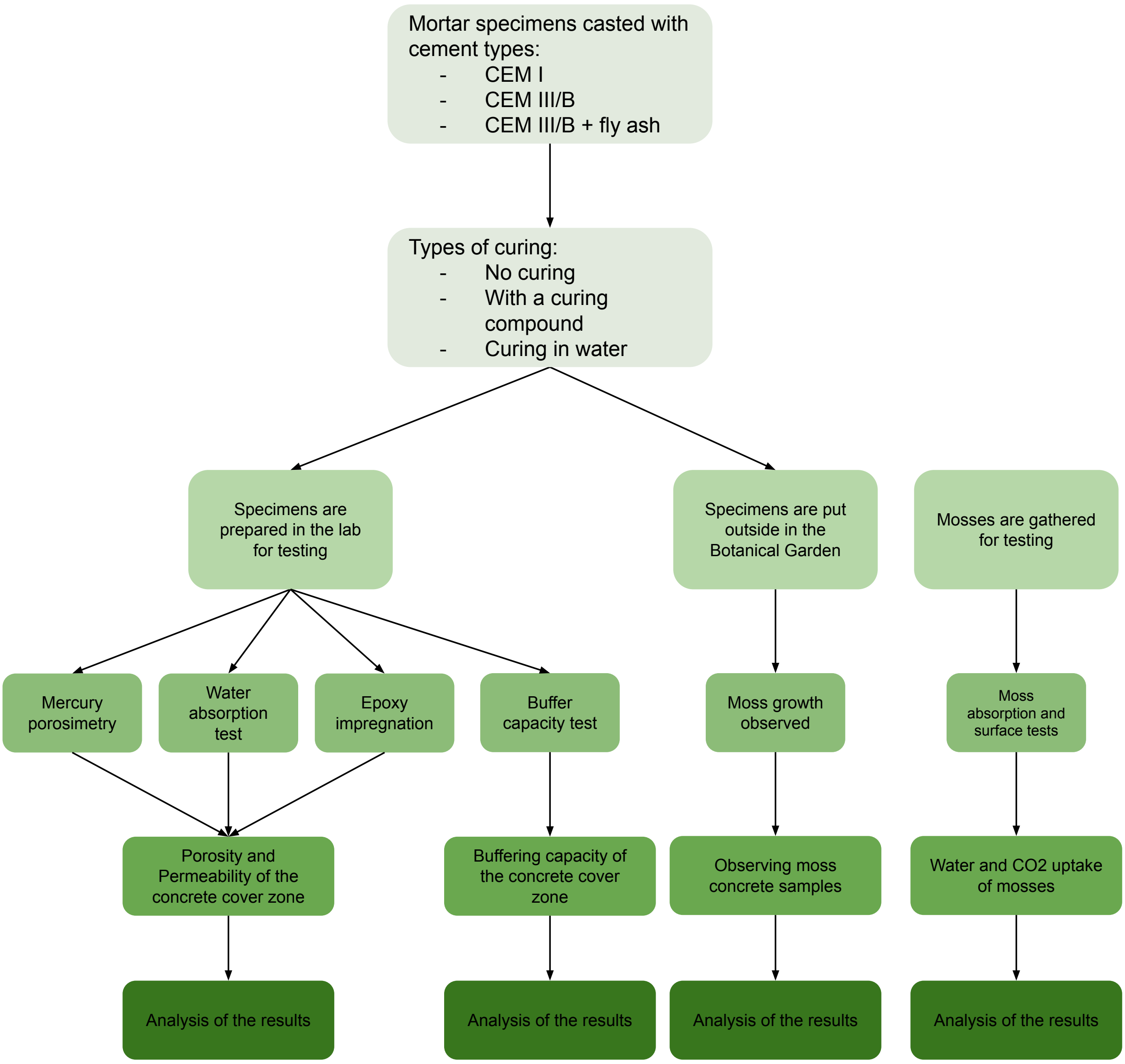


Figure 6.1: Approach of this thesis *(Author's figure)*

The following experiments will be executed, visualised in figure 6.1:

1. **Mercury intrusion porosimetry (MIP)** - With this technique information on the porosity of the mortar specimen can be determined. The pore distribution and the pore shape of the mortar specimens can be analysed [122]. This test will be executed according to NEN-ISO 15901 [123].
2. **Water absorption test** - This test is created by the CROW committee, and is based on soil sample investigations. With this test the water absorption and retaining capacity of the specimens can be found, and quantified [29].
3. **Epoxy impregnation** - Specimens will be impregnated with an epoxy, and held under UV light. This will give a qualitative insight in the porosity of the cover layer.
4. **Carbonation test** - The specimens impregnated with an epoxy will be treated with phenolphthalein, and pictures will be taken to create an understanding of the degree of carbonation.
5. **Buffer capacity test** - This test is created to obtain and compare the buffering capacity of the samples. The amount of acid that is added to maintain a pH of 7 is monitored throughout the time. At the start and the end of the test the pH will be measured.
6. **Moss absorption test** - This test is developed for this research to analyse the water uptake of moss specimens and find the dry weight to surface area conversion (kg/m^2). This can be used to quantify the CO_2 uptake.
7. **Visual observation** - The moss growth on the mortar specimens will be observed, and compared so conclusion can be made with regard to the bioreceptivity of different binder types, curing conditions and growing factors. A part of the samples will be covered with a moss growth promoting substance.

From the data received by these experiments analyses will be made. This to verify if the received data is meaningful and to test if the formed hypotheses are proven correct. The weighting factor of the experiments differ. The water absorption test and buffer capacity test give the leading results, which can be supported by the epoxy impregnation, carbonation test, Mercury Intrusion Porosimetry and the visual observations.

6.2 Mortar specimens

For the experiments mortar prisms will be made that will have the dimension of 40 mm x 40 mm x 160 mm. The choice for mortar specimens instead of concrete specimens has been made to leave out the effect of aggregates. Three different cement types will be used that will differ in clinker quantity. This because it is hypothesized that the clinker content in concrete will influence the properties, and may make the concrete more vulnerable for insufficient curing. The following cement types will be used, their content is illustrated in table 6.1:

1. **CEM I** - This cement type consists of 95-100% clinker, and is called Ordinary Portland Cement. The specimens made of this group will be used as the control group. The used Portland cement is produced by the ENCI, and is manufactured according to EN 197-1 [6]
2. **CEM III/B** - In the Netherlands this type of cement is most commonly used. It consist of a range of 20-34% of clinker and 66-80% of Ground Granulated Blast Furnance Slag (GGBS), and 0-5% of minor constituents according to EN 197-1[6]. The cement type used in this research is fabricated by the ENCI, and the Ground Granulated Blast Furnace Slag content is between 68-73 %
3. **CEM III/B + Fly Ash** - In the codes NEN-EN 206 and NEN 8005 it is specified that when fly ash is added to CEM III/B as bulking agent, a part of the fly ash may be seen as binding agent[71] [70]. For the combination of CEM III/B and fly ash a k-factor of 0.2 can be found, meaning that 1/5th of the fly ash added to the concrete mix can be seen as binding agent and therefore replace CEM III/B [71] [70]. This results in a mix with the lowest amount of clinker that is used in practice. According to research, adding 20% of the amount of cement that is needed as fly ash is used in practice (construction HSL). From this fly ash 1/5th is replacing the cement, and 4/5th will serve as bulking material and thereby replace sand.

Cement type	Name	Clinker (%)	BFS(%)	Fly ash (%)	Additional constituents
CEM I	Portland cement	95-100	0	0	0-5
CEM III/b	Blast furnace cement	27-32	68-73	0	0-5
CEM III/b + fly ash	Blast furnace cement with fly ash	25,9-30,7	65,7-70,6	4	0-4,8

Table 6.1: The composition of the binders used in this research

From these three different binder types, specimens are made with the dimension 40 mm x 40 mm x 160 mm. To mimic the insufficient curing conditions that might happen in practice, a part of the specimens will be air curing (28 days in 20 °C 65% RH), and another part will be cured with a curing compound (after the application of the curing compound 28 days in 20 °C 65% RH). The curing compound that is used is MasterTop CC 713 from BASF, and is based on paraffin and chlorinated rubber. This is a type I liquid membrane-forming compound, that meets the requirements of ASTM C 309 [124]. The amount that is recommended by the manufacturer is spread on the surface of the specimen with a brush. The curing compound is applied a couple of hours after casting on the side that is not covered by formwork, according to the recommendations of the manufacturer. The curing compound is spread on the other sides after demoulding. The last part of the specimens will serve as a control group and cure under standard testing conditions, NEN-EN 12350-1, for 28 days in water in the laboratory [125].

An overview of the number of specimens that are used per experiment can be seen in table 6.2. Each cement binder will have three different curing conditions. The specimens used for the water absorption test will be made in threefold, the other specimens will be made double.

Tests	Air curing	Curing compound	28 day curing
Water absorption and drying test	3 per cement type	3 per cement type	3 per cement type
Mercury intrusion porosimetry and buffer capacity test	3 per cement type	3 per cement type	3 per cement type
Moss growth	2 per cement type	2 per cement type	2 per cement type
Moss growth with added nutrients and spores	2 per cement type	2 per cement type	2 per cement type
Epoxy impregnation & carbonation testing	1 per cement type	1 per cement type	1 per cement type
Total number of specimens	10 per cement type	10 per cement type	10 per cement type

Table 6.2: Number of specimens fabricated per test

In table 6.3 the total amount of specimens that need to be casted per batch can be found. This will be the starting point for the fabrication of the specimens. Three batches will be created, in which each batch will consist of a different binder. The manufactured mortar specimens are visualised in figure 6.2.

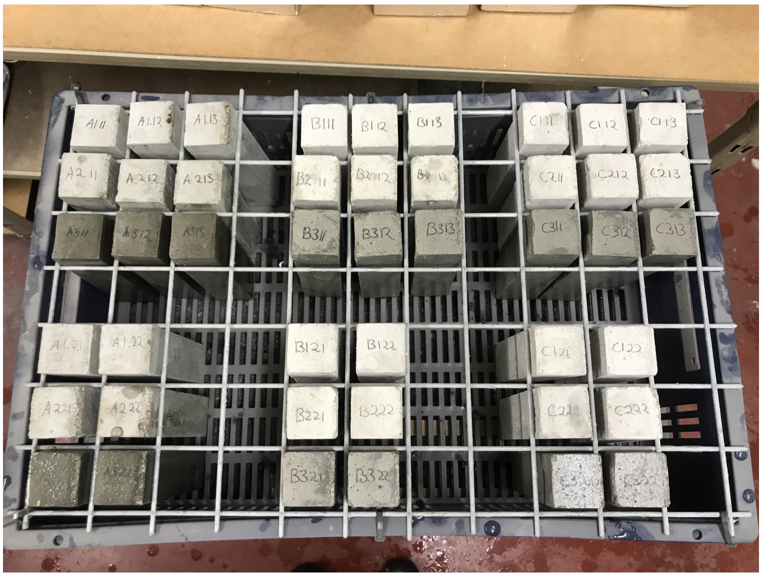


Figure 6.2: Manufactured mortar specimens for this research *(Author's figure)*

Batches	Fabricated specimens	w/c factor
Batch A: CEM I	30	0.55
Batch B: CEM III/b	30	0.55
Batch C: CEM III/b + fly ash	30	0.55
Total number of specimens	90	

Table 6.3: Number of specimens produced per batch

The ratio's given in NEN-EN 196-1 are used to calculate the necessary materials per batch. This is the following: for three specimens of dimension 40 mm x 40 mm x 160 mm, 450 gram cement, 1350 gram of sand, and 225 gram of water is needed, or in other words, the ratio cement:sand:water is 1:3:0.5 [126]. However, this ratio is used for mortar with a w/c ratio of 0.5, while in this research the choice has been made to create specimens with a w/c ratio of 0.55. This leads to an elevated amount of water of 248 gram per three fabricated specimens. The choice has been made to increase the ratio cement:sand to 1:3.3, to avoid segregation during the production process. The material proportion used in this research can be found in table 6.4, in weight (kg) and percentage of total weight (%).

Batches	CEM I (kg)	CEM III/B (kg)	Water (kg)	Sand (kg)	Fly ash(kg)
Batch A: CEM I	20,6 % (4,50)	0	11,34 % (2,475)	68,04 % (14,85)	0
Batch B: CEM III/b	0	20,6 % (4,50)	11,34 % (2,475)	68,04 % (14,85)	0
Batch C: CEM III/b + fly ash	0	19,8 % (4,32)	11,34 % (2,475)	64,74 % (14,13)	4,12 % (0,90)

Table 6.4: The material proportion used in this research, in weight (kg) and percentage of total weight (%)

6.3 Testing methods

In this section the experiments that have been conducted for this research are elaborated. For each test the execution method and the expected results are given.

6.3.1 Absorption tests and drying behaviour

In these tests the absorption capacity and drying behaviour of the specimens will be measured, which will give an insight in the porosity and permeability of the samples. The experiment will be executed in the laboratory of SGS Intron, according to the absorption tests performed in the CROW investigation of moss concrete [29].

Method
The first 10 mm from the surface of the side of the prism that was not covered by formwork during casting is cut, creating a sample that is referred to as the "surface part" (s). The internal part (20-30 *mm* from the top) of the specimen is also cut, which will give a sample that is referred to as the "core part" (c). This is illustrated in figure 6.3.

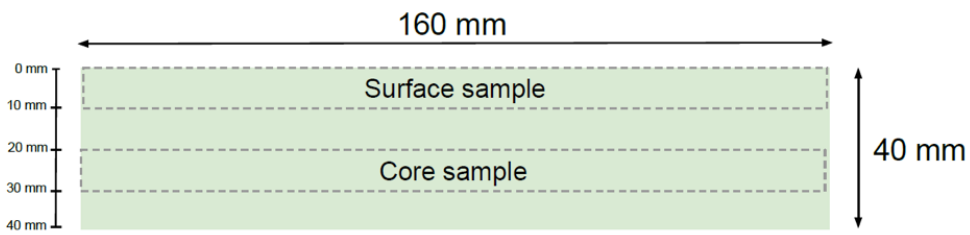


Figure 6.3: Samples obtained for the absorption and drying test *(Author's figure)*

The obtained samples are first dried in a ventilated oven for 48 hours at 37 °C, and subsequently weighted (W_{dr}). Than the samples are submerged in a water container at 20 °C. After 24 hours the samples will be taken out of the water, weighted ($Wwet$) and put back in the ventilated oven at 37 °C. At t = 0 hour, 1, 2, 4, 6 and 24 hour the weight of the sample will be measured. This will give an insight in the drying behaviour of the samples.

The water absorption of the samples is calculated as follows:

$$Water\ absorption\ (\%) = \frac{Wwet - Wdr}{Wdr} \times 100\% \tag{6.1}$$

W_{dr} = Initial drying weight after two days of drying (g), W_{wet} = Weight after 1 day in the water container at t=0 (g)

The drying behaviour will be calculated with the following expression for the moisture content at time=t:

$$Moisture\ content\ at\ time\ t\ (\%) = \frac{Wt - Wdr}{Wdr} \times 100\% \tag{6.2}$$

W_{dr} = Initial drying weight after two days of drying (g), W_t = Weight during drying at t=t (g)

The moisture loss due to drying can be calculated over time with formula 6.3. The hourly moisture loss will be calculated with formula 6.4. The hourly moisture loss is a measure for the permeability of a sample.

$$Moisture\ loss\ at\ time\ t\ (\%) = \frac{Wt - Wwet}{Wwet} \times 100\% \tag{6.3}$$

$$Rate\ of\ moisture\ loss\ at\ time\ t\ (\%) = \frac{Wt_2 - Wt_1}{Wt_1 \times (t_2 - t_1)} \times (t_2 - t_1) \times 100\% \tag{6.4}$$

W_t = Weight during drying at t=t (g), W_{wet} = Weight after 1 day in the water container at t=0 (g), W_{t1} = Weight during drying at t=t_1 (g), W_{t2} = Weight during drying at t=t_2 (g), t_1<t_2, and the values for t are in hours.

Expected results
The curing method will influence the hydration process, which will lead to different concrete properties, as explained

in section 3.5 *concrete properties*, and is illustrated in figure 3.15 on page 26. This leads to the expectation that the specimens that have been air cured will absorb most water, while the specimens that have been cured in water will absorb the least amount of water. The cement type will also have an influence on the moisture behaviour of concrete. It is expected that specimens that consist of CEM III/B and fly ash and were air cured will absorb most moisture. This is because the alternative binders in this cement didn't have enough time to hydrate when the molds were taken off, leading to a porous and permeable cover zone. It is expected that the internal samples will absorb less water than the surface samples made from the same specimen.

6.3.2 Epoxy impregnation and carbonation

To visualise the effect of the curing conditions, an epoxy impregnation and carbonation test is executed after three months. The epoxy impregnation will visualise the pores that are present under ultra violet (UV) light. An pH-indicator is used to observe the degree of carbonation after three months.

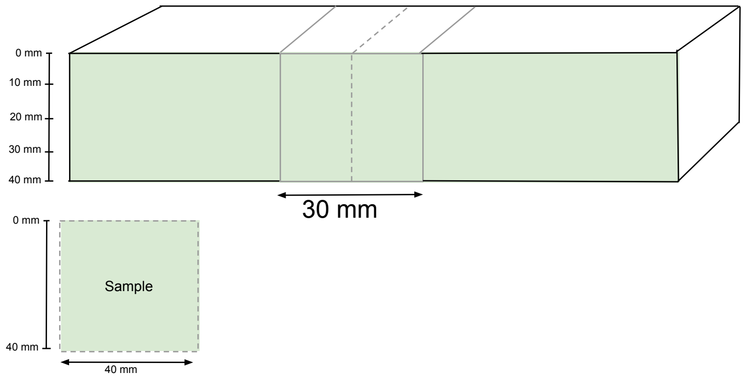


Figure 6.4: Samples obtained for the epoxy impregnation *(Author's figure)*

Figure 6.5: Specimens impregnated with epoxy *(Author's figure)*

Method
After 28 days of curing, specimens will be placed in a room of 20 °C and 65 % RH for another two months. After three months, a middle section of 30 *mm* will be cut from the specimens, visualised in figure 6.5. The moisture will be taken out of the specimens with a vacuum pump, and a liquid fluorescence epoxy is brought into the specimens. This epoxy will be absorbed in the parts were the moisture and air used to be. After two days the epoxy is hardened, and the specimens are cut through the middle. One side will be placed under UV light, where it is visualised qualitatively how far the epoxy has entered the specimen. At the other side of the specimens phenolphthalein is applied with a brush, which is an pH indicator and will color pink when the pH is between 8,2-10. The colorless part of the specimen indicates that the pH is below 8,2, and therefore has been carbonated. This is also visualised qualitatively with pictures.

Expected results
It is expected that the samples that have been air cured will have most epoxy entering the sample, and the least amount of pink color. The samples that have been cured in water are expected to have a very small colorless layer compared to the other specimens, and will have least amount of epoxy entering the samples. The behaviour of the specimens cured with a curing compound is expected to be in between of the behaviour of the other two curing conditions. The effect of the cement type is expected to have less effect on the results. However, it is expected that CEM I will have the least amount of epoxy entering the sample, and the smallest colorless layer at the outside of the samples surface, compared to the other cement types.

6.3.3 Mercury Intrusion Porosimetry

During the Mercury Intrusion Porosimetry test, the pore size and pore distribution will be measured.

Method
After 28 days of curing, the top layer of the specimens are cut, as is illustrated in figure 6.6. Subsequently, the samples are broken into smaller pieces with a hammer. The moisture has to be removed from the sample to be able to perform the Mercury Intrusion Porosimetry, therefore the samples are dried in a freeze drying in the microlab at the Technical University Delft. Although freeze drying will result in a slight change in the micro-structure, it seems that this is the best option for this research.

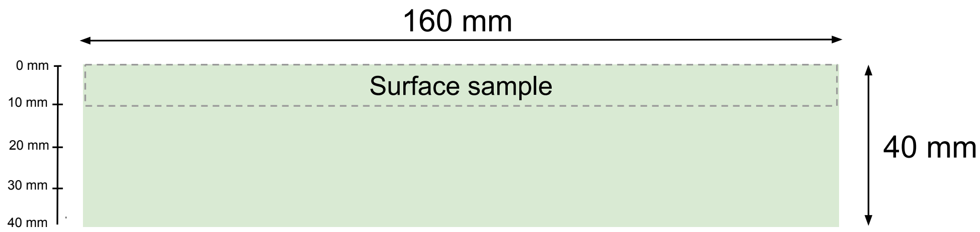


Figure 6.6: Samples obtained for the Mercury intrusion porosimetry *(Author's figure)*

Expected results
It is expected that samples that contain a low amount of clinker will be more porous than specimens with a high clinker content. It is expected that samples that consist of CEM I will have more capillary pores, and less gel pores, while samples containing CEM III/B or CEM III/B + fly ash are expected to contain more gel pores and less capillary pores. This is because of the hydration processes taking place in the mortar samples, as is explained in section 3.3 *Hydration processes* on page 18.

6.3.4 Buffer capacity test

In the buffer capacity test the response of the specimens against added acid will be measured. As is explained in chapter 5 *Hypothesis formation*, on page 46, concrete with a high buffering capacity will have enough calcium hydroxide in its pore solution that can react with acid and CO_2 from the outside environment. The influence of the clinker-content and curing conditions on the buffering capacity will be found and compared in this experiment. This experiments will be performed in threefold, to give accurate and meaningful results, and are executed with a titration setup in the Microlab at CITG.

Figure 6.7: The titration set up for the buffer capacity test *(Author's figure)*

Method
The top layer of the prisms will be cut off, and the prisms will be cut in four pieces, which leads to surface samples

of 40x40x10 mm, as can be seen in figure 6.8. Subsequently, the samples are grinded to a powder in a ball vibrator, and from each sample 0,5 gram will be used.

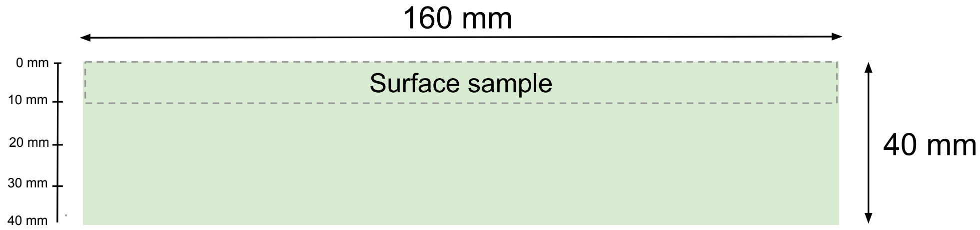


Figure 6.8: Samples obtained for the buffer capacity test *(Author's figure)*

At t=0 minutes, 150 mL of water will be added to the 0,5 gram of the sample, the reaction that will take place can be seen in formula 6.5. At t=1 minute, the pH is measured, which will give the pH at the start (pH_{start}).

$$Ca(OH)_2 \longrightarrow Ca^{2+} + 2OH^- \tag{6.5}$$

The timer will be restarted, and at t=0 minute acid is added to obtain a pH of 7. The acid that is used is hydrochloric acid, with a molarity of 0.1 mol/l. In the hydrochloric acid the following reaction has taken place:

$$HCL + H_2O \longrightarrow H_3O^+ + Cl^- \tag{6.6}$$

The acid that is needed to keep the pH at 7 will be measured every minute, until 20 minutes have passed. In the solution the following reaction will take place:

$$H_3O^+ + OH^- \longrightarrow 2H_2O \tag{6.7}$$

No more acid is added after 20 minutes, and at t=22 minutes the pH will be measured. This will give the value for the pH at the end of the 20 minute buffering capacity test (pH_{end}). At t=22 minutes, 0,2 mL of hydrochloric acid is added to the solution, and the pH will be measured at t=23 minutes. This will give the value for the pH after extra acid has been added. The pH drop after the extra acid is added will be calculated with the following formula 6.8:

$$pH\ drop\ after\ extra\ acid\ = pH_{drop} = pH_{end} - pH_{acid} \tag{6.8}$$

pH_{end} = pH at t=22 minutes, after two minutes without adding acid, pH_{acid} = pH at t=23 minutes, one minute after adding 0,2 mL of hydrochloric acid.

Expected results
It is expected that the specimens containing most clinker will have the best buffering capacity. This is shown as the highest pH at the start, the most acid that is added every minute, and the highest pH at the end. The pH drop should also be the smallest for these specimens. The effect of the curing conditions is expected to have a smaller influence on the buffering capacity, specimens that have been cured in water are expected to give the highest buffering capacity.

6.3.5 Visual observation

Moss will be grown on specimens with knowledge from the first part of the thesis and methods found in literature. To create an environment on which mosses and other organisms can grow, the alkalinity of the specimens has to drop at the cover [37]. This is achieved by adding dairy products on the surface layer of the mortar. To speed up the formation of moss growth on the specimens, spores of the wanted type of moss are added [127].

Figure 6.9: The location of the specimens in the botanical garden of Delft University of Technology *(Author's figure)*

Method
Specimens are put in the botanical garden of Delft University of Technology, visualised in figure 6.9. Each combination of binder type and curing conditions has four specimens. A moss promoting substance is added on two of the four specimens, that consists of:

- Spores of a pioneer moss type, taken from a concrete structure that has abundant pioneer moss growth
- Buttermilk
- Water
- Sugar

Periodically pictures will be taken to monitor the changes on the surface of the specimens that occur over time.

Expected results
It is expected that mosses will be able to grow better on specimens that contain a low amount of clinker. This is expected because of the lower alkalinity of the pore solution. From the low-clinker content specimens, the ones that didn't receive any curing should be the most bioreceptive.

6.3.6 Moss experiments

To quantify some of the properties of moss concrete, several experiments have been executed. Two moss sorts have been tested, namely the *Tortula Muralis*, which is a pioneer moss and grows in cushions on concrete, and the *Hypnum Cupressiforme*, which forms a moss mat on the concrete, and is often found after several years. In order to be able to quantify several moss properties the water absorption and dry weight (kg) to moss surface (m2) conversion has to be known.

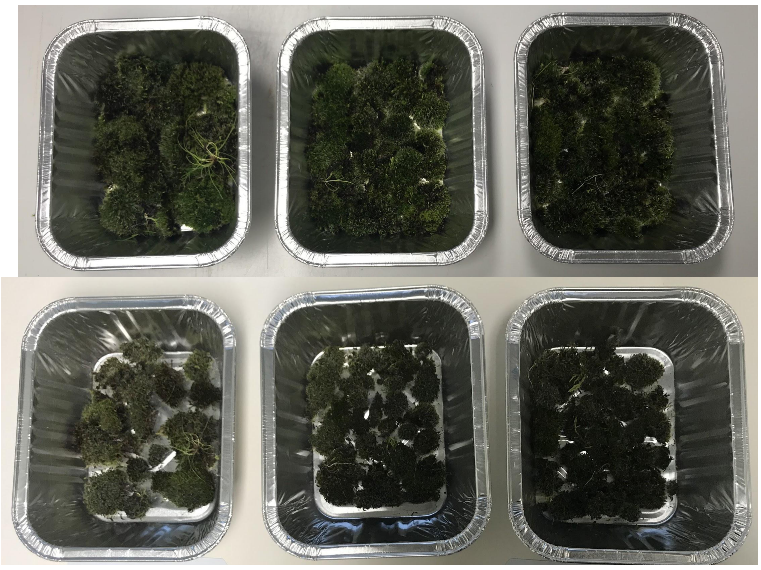


Figure 6.10: The moss specie Tortula Muralis before and after 24 hours of drying *(Author's figure)*

Method
Mosses were placed in a tray filled with water, and stored for 24 hours in a cold storage (13 °C), to mimic the outside conditions where the mosses have been captured. After 24 hours the mosses were taken out of the water, the large water drops were wiped off, and the mosses were placed in a new dry tray with a known surface area. This tray was put in a ventilated oven at 40 °C, whereby the weight has been measured at t=0, 1, 2, 4, 8 and 24 hours. After 24 hours the mosses were declared dry.

The water absorption of the samples has been calculated as follows:

$$Water\ absorption\ (\%) = \alpha = \frac{Wwet - Wdr}{Wdr} \times 100\% \tag{6.9}$$

α = water absorption per moss species (%), W_{wet} = Weight after 1 day in the water container at t=0 (g), W_{dr} = Dry weight at the end of the experiment t=24 hours (g).

The moisture loss due to drying has been calculated over time with formula 6.10. The hourly moisture loss is a measure for the permeability of a sample, and has been calculated with formula 6.11.

$$Moisture\ loss\ at\ time\ t\ (\%) = \frac{Wt - Wwet}{Wwet} \times 100\% \tag{6.10}$$

$$Rate\ of\ moisture\ loss\ at\ time\ t\ (\%) = \frac{Wt_2 - Wt_1}{Wt_1 \times (t_2 - t_1)} \times 100\% \tag{6.11}$$

W_t = Weight during drying at t=t (g), W_{wet} = Weight after 1 day in the water container at t=0 (g), W_{t1} = Weight during drying at t=t_1 (g), W_{t2} = Weight during drying at t=t_2 (g), t_1<t_2, and the values for t are in hours.

The dry weight to surface ration for each moss type has been calculated with the following formula 6.12:

$$Dry\ weight\ to\ surface\ ratio\ \ (kg/m^2) = \epsilon = \frac{Wdry}{Atray} \times 100\% \tag{6.12}$$

W_{dr} = dry weight at the end of the experiment t=24 hours (kg), A_{tray} = area of the tray (m^2), ϵ = dry weight to surface ratio (kg/m^2)

Expected results It is expected that the specimens absorb relatively a large amount of water compared to the mortar specimens. Thereby it can not be foreseen what the differences in water absorption and dry weight between the two moss species that have been tested are.

Chapter 7

Results

In this chapter the results of the experiments conducted for this research, to test the hypothesises, are given. The execution of the absorption test, drying test, epoxy impregnation, carbonation, Mercury Intrusion Porosimetry, buffer capacity test, visual observation, and moss experiments are explained in chapter 6 *Experiments* on page 49.

7.1 Absorption tests

In figure 7.1 the water absorption of the surface of the samples is illustrated, categorized on binder type. The surface of CEM III/B + fly ash has relatively the largest difference in water absorption between the curing conditions air cured and water cured. The absorption of the surface will increase with 98,56 % for CEM III/B + fly ash samples when air cured instead of water cured. This increase in absorption is 80,89 % for the surface of CEM III/B and 29,09 % for the surface of CEM I samples when air cured instead of water cured. The low-clinker content samples (CEM III/B and CEM III/B + fly ash samples) treated with a curing compound have a similar water absorption as the air cured samples. In figure 7.2 the average absorption per binder type is given. It can be seen that a relative large standard deviation is found for the average absorption of CEM III/B and CEM III/B + fly ash samples, compared to a relative smaller standard deviation for CEM I samples. A large standard deviation indicates a large difference between different curing conditions. The average absorption of the surface samples per binder type is 7,07 % for CEM I, 7,68 % for CEM III/B and 7,53 % for CEM III/B + fly ash.

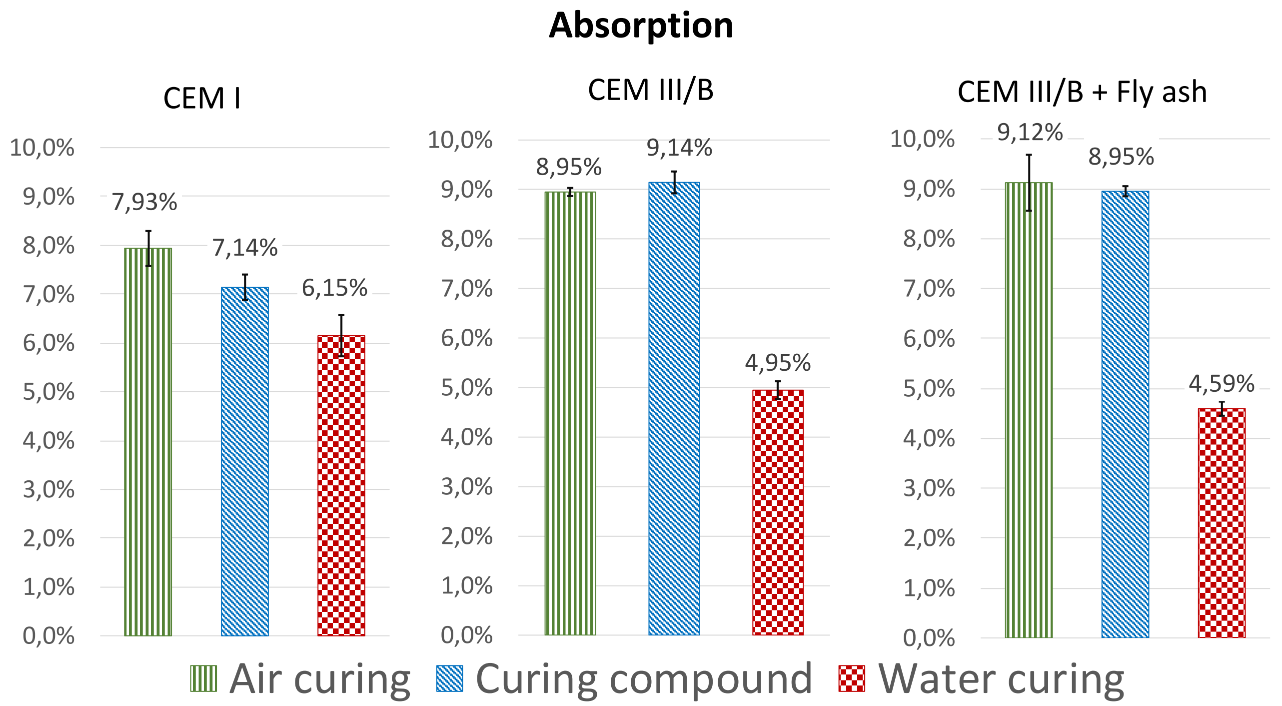


Figure 7.1: The water absorption of the surface of samples made from CEM I, CEM III/B and CEM III/B + fly ash that have been air cured, cured with a curing compound, and water cured. The surface of CEM III/B + fly ash specimens have relatively the largest increase in water absorption between the curing conditions water cured and air cured. The samples of CEM III/B and CEM III/B + fly ash behave similar when cured with a curing compound instead of air cured.

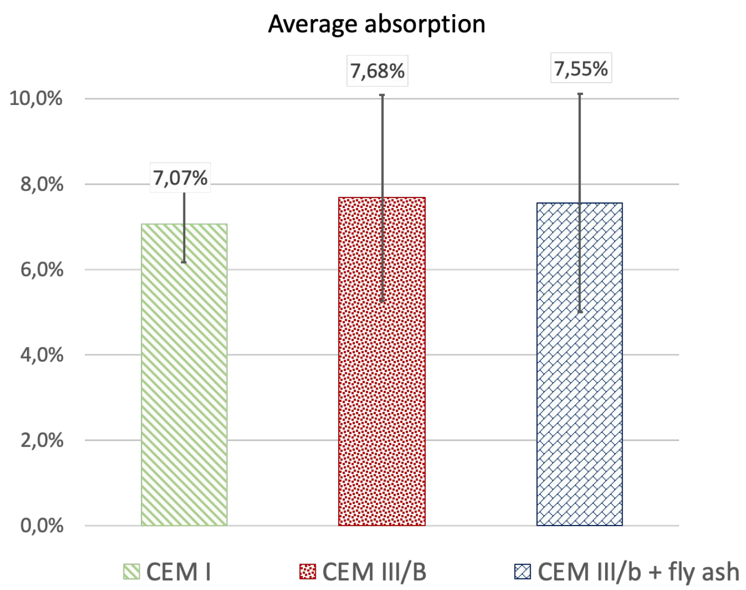


Figure 7.2: The average water absorption of the surface of all specimens with standard deviation bar, per binder type. The relative small standard deviation bar of CEM I samples shows that these samples behave most homogeneous, despite the different curing conditions.

The average water absorption of surface samples is 8,67 % for air cured samples, 8,41 % when the samples are cured with a curing compound, and 5,23 % for samples cured in water. This, together with the average absorption of the core samples, is visualised with standard deviation bars in figure 7.3. This shows large standard deviation bars for samples cured with a curing compound and a similar water absorption for the core and surface samples, where the core samples take up slightly more water.

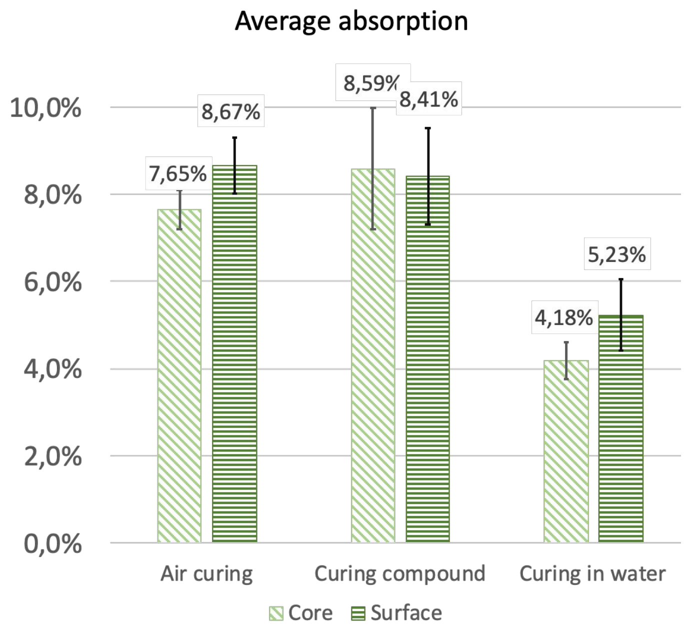


Figure 7.3: The average water absorption and standard deviation of the core and surface of specimens, per curing condition. Specimens cured with a curing compound have a relatively large standard deviation bar, and the core of samples cured with a curing compound absorbs on average slightly more water than the surface.

In figure 7.4 the water absorption of the surface and core of the specimen can be found, categorised on binder type. It can be seen that the low-clinker content specimens behave relatively similar for each curing condition. When comparing the water absorption of the core and surface, it can be seen that the surface absorbs more water than the core, except for samples cured with a curing compound.

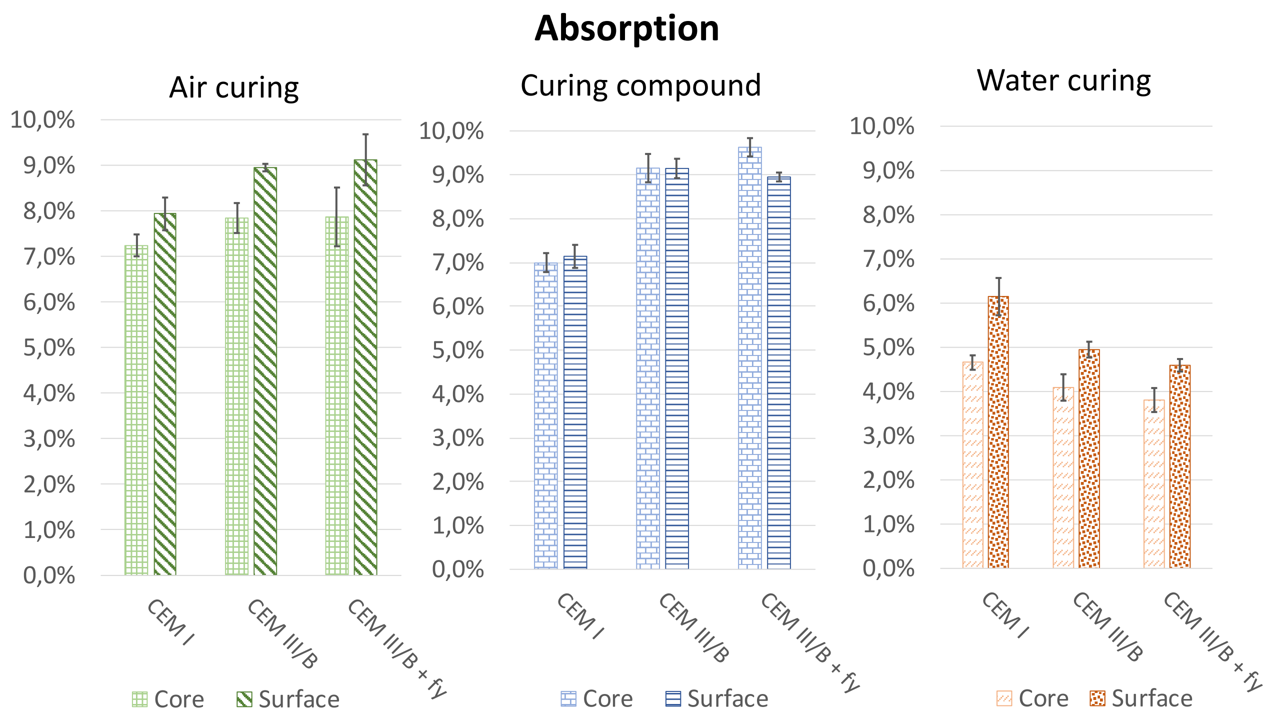


Figure 7.4: The water absorption of the core and surface of specimens that are air cured, cured with a curing compound, and water cured, that consist of CEM I, CEM III/B and CEM III/B + fly ash. The core of specimens cured with a curing compound absorbs a similar or higher amount of water than the surface of these specimens.

7.2 Drying behaviour

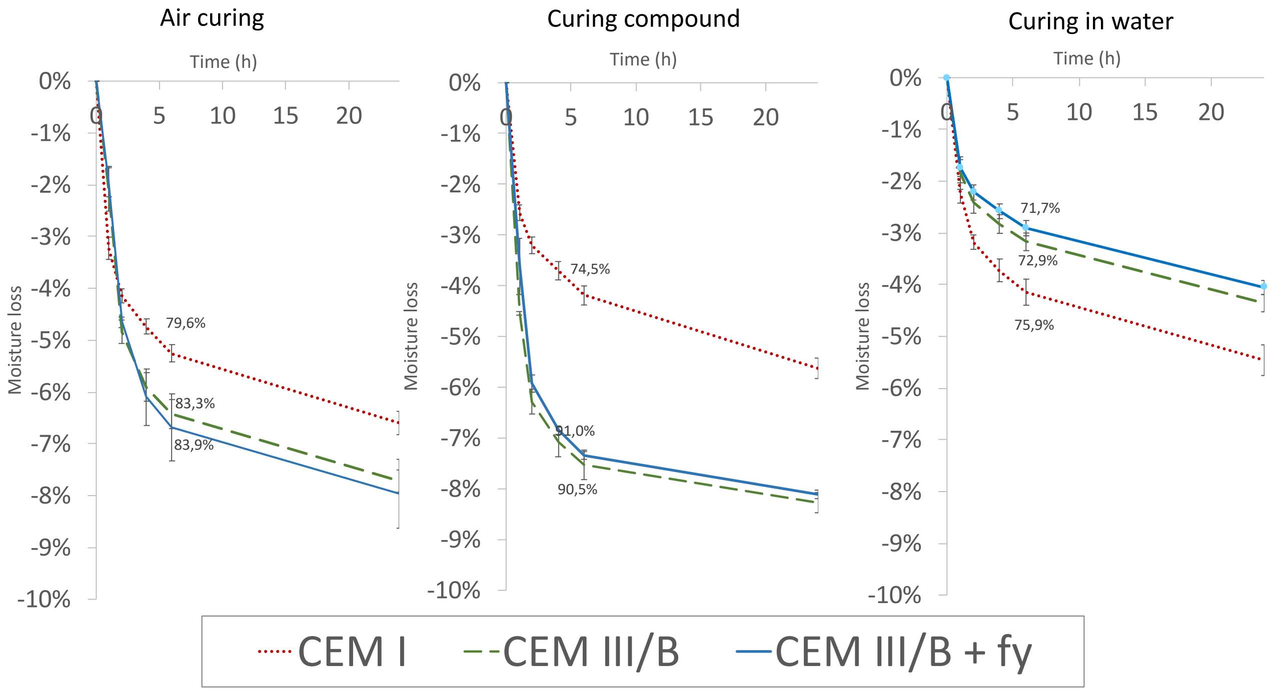


Figure 7.5: The moisture loss from the surface of the specimens over 24 hours when air cured, cured with a curing compound, and cured in water for specimens that consist of CEM I, CEM III/B and CEM III/B + fly ash. The moisture loss after 6 hours as percentage of the total moisture loss after 24 hours is given for each specimen, which is a measure of the permeability.

In figure 7.5 the moisture loss from the surface of the specimens over 24 hours is given. This is a measure of the porosity and the permeability of the sample. The surface of specimens cured in water loses relatively least moisture compared to specimens cured with other curing conditions. When air cured, the surface of CEM III/B + fly ash specimens loses most of its moisture and the surface of CEM I specimens the least. This is the other way around when the specimens have been cured in water, visualised in figure 7.5.

The surface of samples that have a low-clinker content (samples that consist of CEM III/B and CEM III/B + fly ash) loses more moisture when the samples are cured with a curing compound instead of air cured. For each specimen, the percentage of moisture loss as part of the total moisture loss is given at t=6 hours in figure 7.5. This is an indication of the permeability, thereby showing that the low-clinker content specimens have the highest permeability when cured with a curing compound, also shown in table 7.1. In *Appendix A - Results* on page 115 more results for the drying behaviour aregiven.

Binder type	**Air curing**	**Curing compound**	**Water curing**	**Average (SD)**
CEM I	79,6 %	74,5 %	75,9 %	76,67 % (2,63 %)
CEM III/b	83,3 %	**90,5 %**	72,9 %	82,36 % (9,12 %)
CEM III/b + fly ash	83,9 %	**91,0 %**	71,7%	82,06 % (9,55%)
Average (SD)	82,25 % (2,33 %)	85,34 % (9,4 %)	73,46 % (2,18 %)	

Table 7.1: The moisture loss after 6 hours for each binder type and curing condition as percentage of the total moisture loss after 24 hours.

7.3 Epoxy impregnation

The result of the epoxy impregnation, executed after three months and described in section 6.3.2 *Epoxy impregnation* on page 55, is given in figure 7.6. The epoxy is impregnated from the surface. How far the epoxy has penetrated the sample is an indication of the porosity and permeability of the sample.When the specimens are held under ultra violet (UV) light, the fluorescent part shows the location of the epoxy. It can be seen in figure 7.6 that samples that have been cured in water have the lowest quantity of epoxy penetrated from the surface. This is in line with the results of the absorption test and the drying behaviour test. The samples that consist of CEM III/B and CEM III/B + fly ash show an increase in epoxy penetrated from the surface when cured with a curing compound, compared to when the samples are air cured.

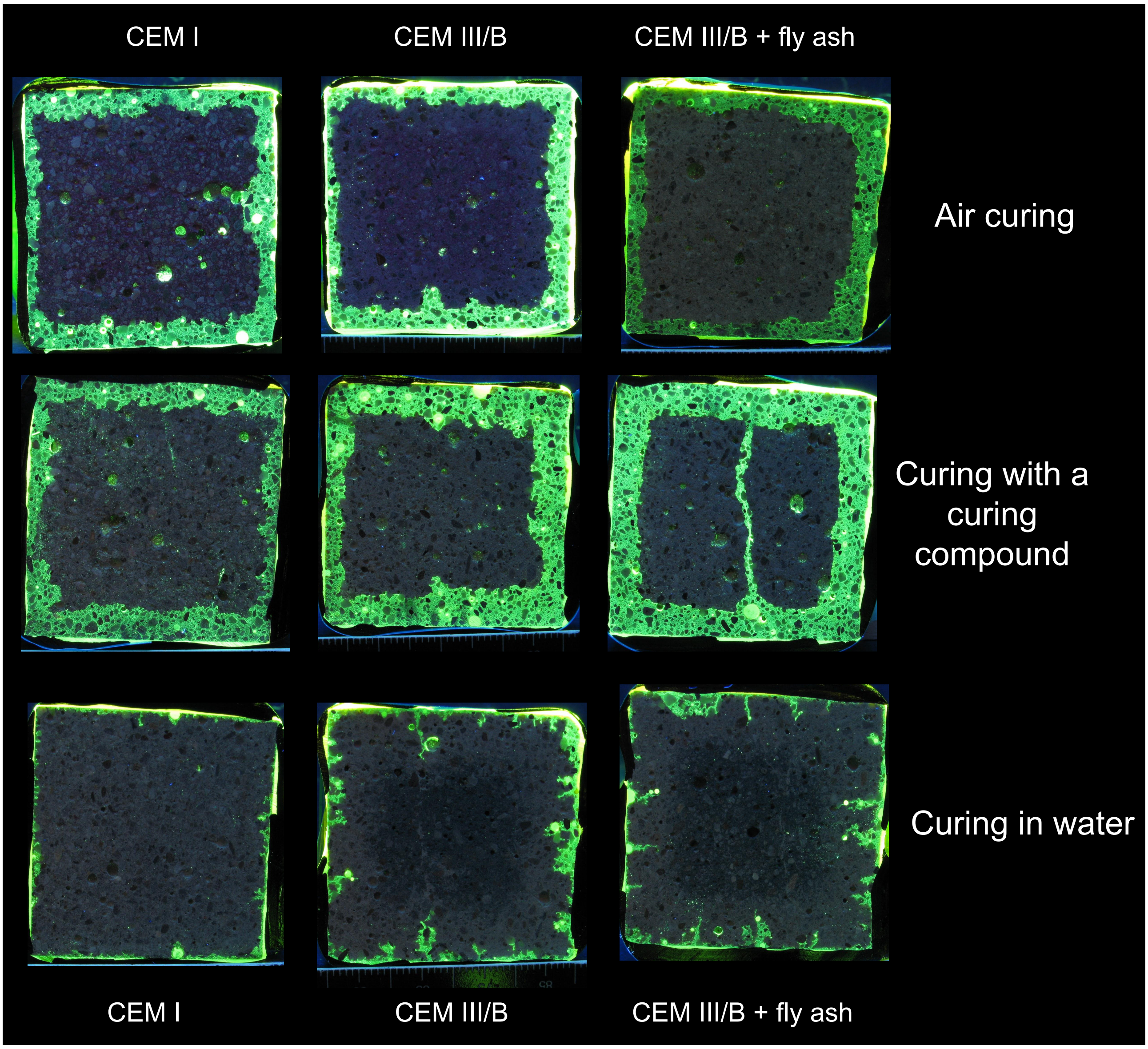


Figure 7.6: The location of the epoxy penetrated from the surface, made visible under UV light, gives an indication of the porosity and permeability of the specimens. The samples that consist of CEM III/B and CEM III/B + fly ash show an increase in epoxy penetrated from the surface when cured with a curing compound, compared to when the samples are air cured.

7.4 Carbonation

The result of the carbonation test, executed after three months and described in section 6.3.2 *Carbonation* on page 55, is given in figure 7.7. The pink color indicates a high pH, therefore the colourless parts show where carbonation has occurred, since carbonation lowers the pH. It can be seen that samples cured in water and samples that consist of CEM I show most coloring of pink, meaning that these samples have had the least carbonation. The low-clinker content samples (CEM III/B and CEM III/B + fly ash) show most carbonation when cured with a curing compound.

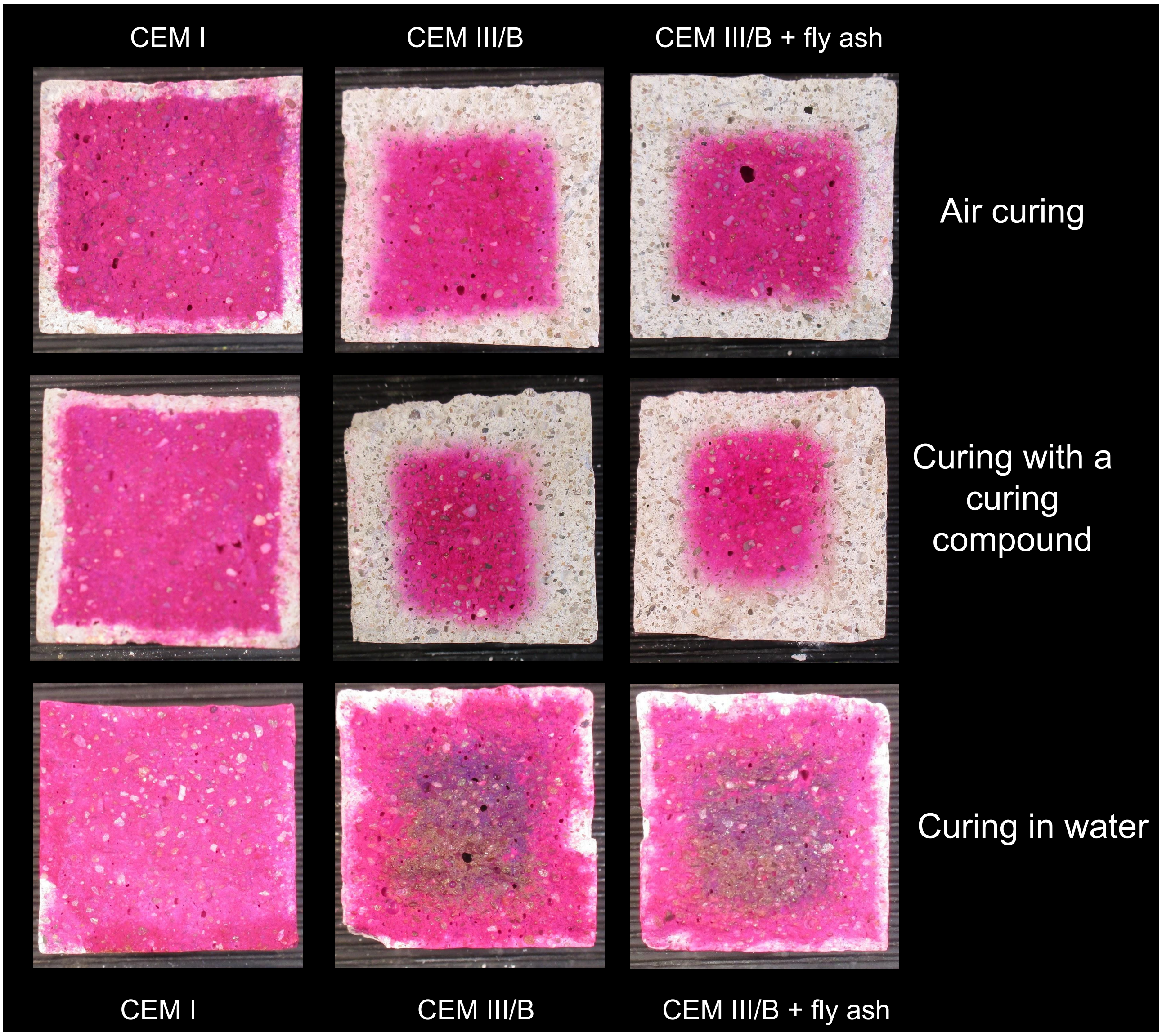


Figure 7.7: Results of carbonation tests. The uncolored part shows the part of the concrete that is carbonated. Low-clinker conctent samples that have been cured with a curing compound show relatively more carbonation than air cured samples.

7.5 Mercury intrusion porosimetry

The Mercury Intrusion Porosimetry (MIP) machine unfortunately broke down after three measurements. Therefore, the results of only three samples have been collected. The samples that have been tested successfully were all air cured. The results are given in figure 7.8. The height of the line in figure 7.8 indicates the quantity of pores at that specific pore access diameter (μm). Two peaks can be observed for the CEM III/B and CEM III/B + fly ash samples, namely around a pore access diameter of 0,01 μm and between a pore access diameter of 0,4-0,8 μm. The porousness found for CEM I, CEM III/B and CEM III/B + fly ash are respectively 18,2 %, 19,7 % and 21.0 %.

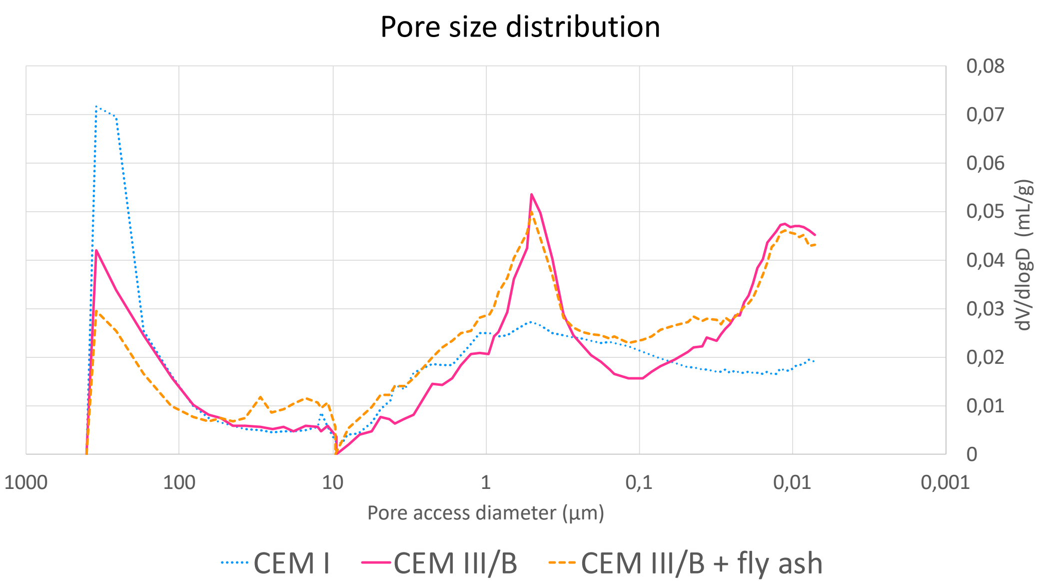


Figure 7.8: The results of three air cured specimens that consist of CEM I, CEM III/B and CEM III/B + fly ash. The height indicates the quantity of pores at a certain pore access diameter (μm).

7.6 Buffer capacity test

In figure 7.9 the pH at the start of the buffer capacity experiment is given. Specimens that consist of CEM I have the highest pH at the start of the experiment compared to specimens made out of other binder types. For each binder type, the specimens that have been cured in water have the highest pH at the start of the experiment. Low-clinker content samples (CEM III/B and CEM III/B + fly ash) have the lowest pH at the beginning of the experiment when cured with a curing compound. CEM III/B + fly ash specimens have a slightly lower pH when cured in water compared to CEM III/B specimens.

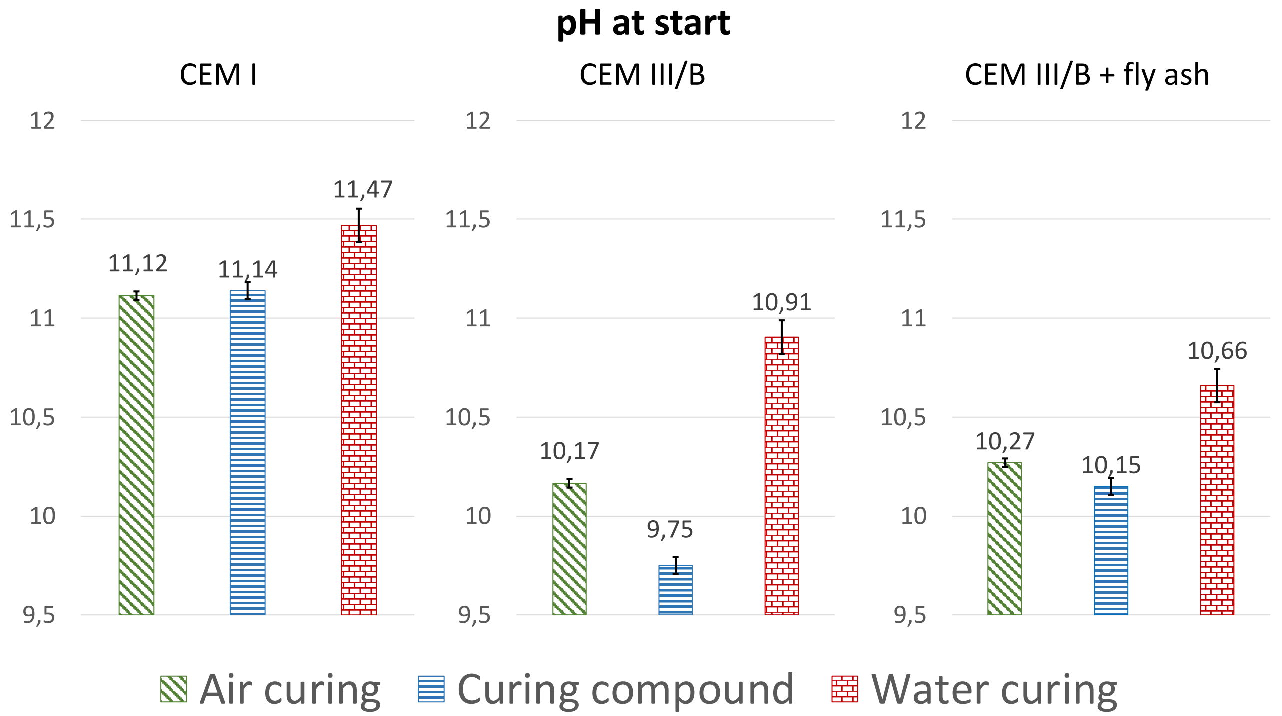


Figure 7.9: The measured pH at the start of the experiment for CEM I, CEM III/B and CEM III/B + fly ash specimens that have been air cured, cured with a curing compound, and cured in water. The samples that consist of CEM I have the highest pH at the start. Specimens cured in water have the highest pH per binder type.

In figure 7.10 the total amount of acid that is added during the experiment can be found. The amount of acid that is added per minute to each solution can be found in appendix A.2 on page 116 where figure A.3 shows the course of the experiment throughout time. CEM I samples can receive most acid during the experiment, especially when cured in water. The samples that consist of CEM III/B or CEM III/B + fly ash show firstly a very similar behaviour, and secondly it seems that the type of curing has relatively a very small influence on the amount of acid that can be added.

A more in depth analysis of the amount of acid that is added can be found in appendix A.2 *Amount of acid added* on page 116.

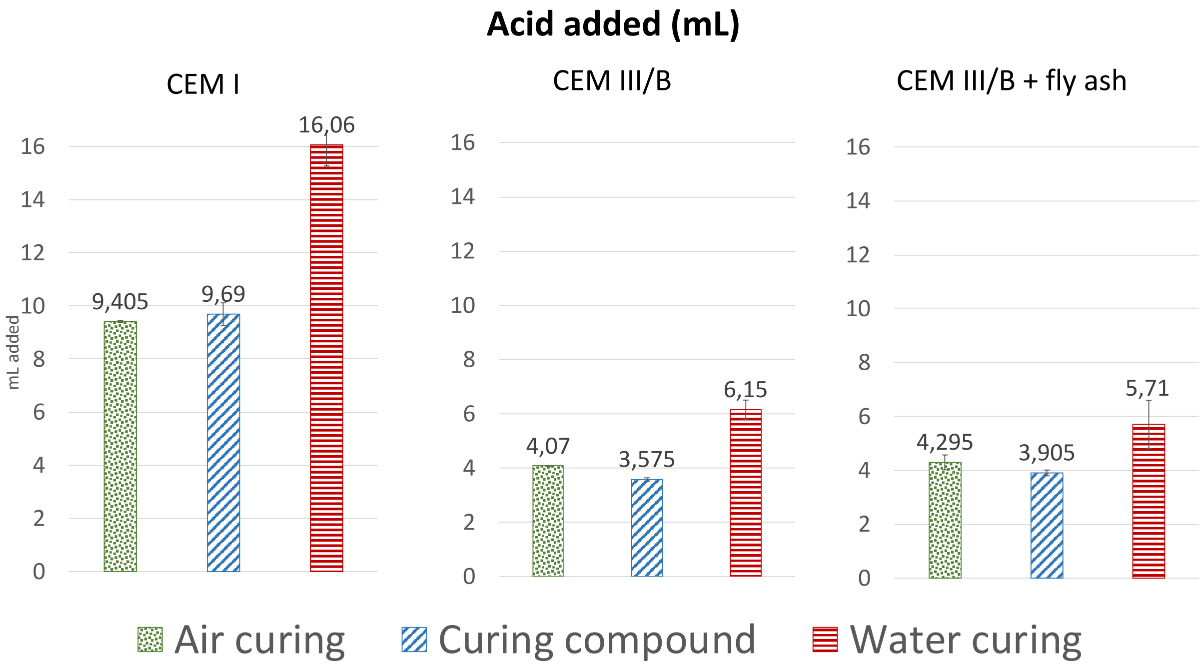


Figure 7.10: The total amount of acid (ml) that could be added during the experiments without changing the pH of the solution. CEM I specimens can receive most acid. For low-clinker content specimens the type of curing has little influence on the amount of acid added.

In figure 7.11 the reaction speed (mL of acid added per minute) during the first five minutes of the experiment is given, per curing condition. For each curing condition, CEM I has the highest reaction speed. It can be observed that the reaction speed of samples that are cured with a curing compound and air cured show relatively very similar behavior for each binder type. Samples that have been curing in water give the highest reaction speed, for each binder type.

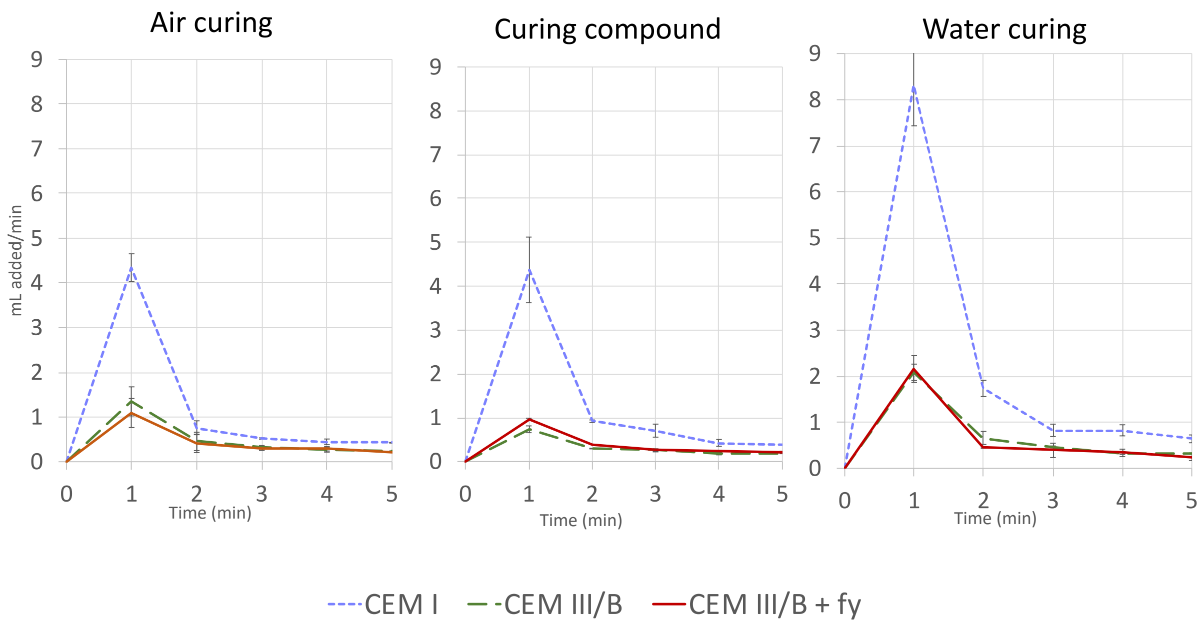


Figure 7.11: The amount of acid (mL) that is added per minute during the experiments. The specimens that consist of CEM I have the highest reaction speed for each curing condition. Samples that are air cured and samples cured with a curing compound show similar reaction kinetics. Specimens cured in water have the highest reaction speed.

The difference between the pH_{end} at t=22 minutes and the pH_{acid} at t=23 minutes, when an additional 0,2 ml of acid is added to the solution, is given in figure 7.12 as the pH_{drop}. CEM I specimens have the lowest pH_{drop}, especially when cured in water. Differences can be found in the pH_{drop} when the specimens have been cured in different conditions. However, these differences are relatively small compared to the differences observed when different binder types are being used.

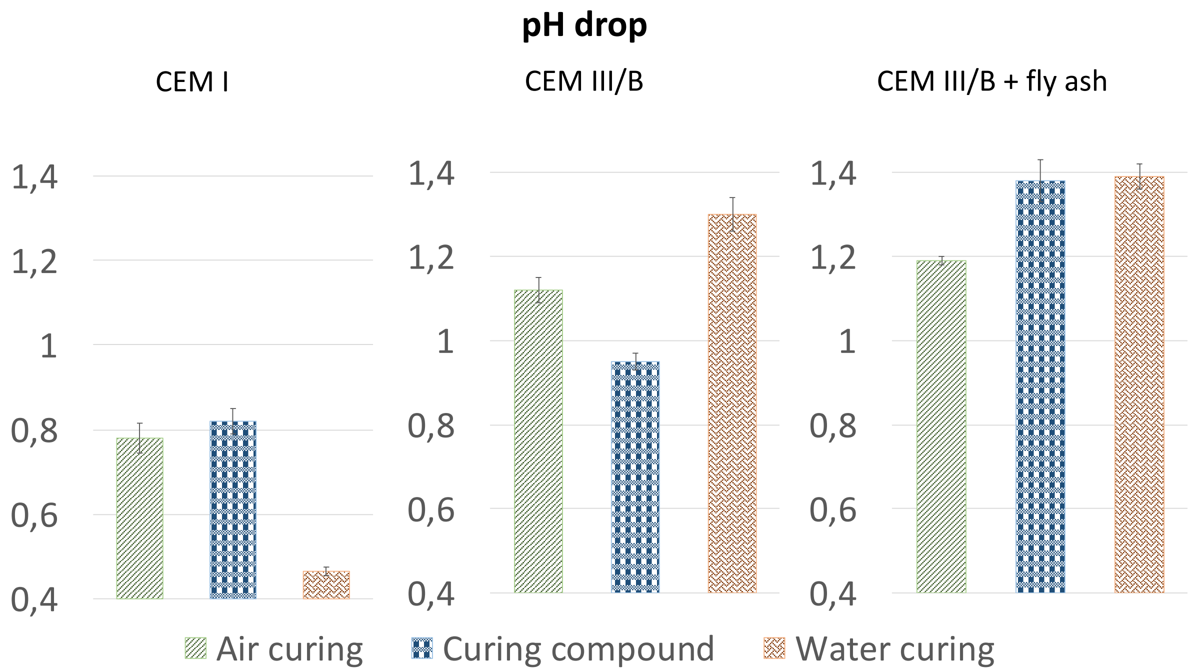


Figure 7.12: The pH_{drop} measured before and one minute after adding extra acid at the end of the experiment. CEM I specimens have the lowest pH_{drop}, especially when cured in water. The differences in pH_{drop} are relatively small for different curing conditions compared to the differences observed when different binder types are being used.

7.7 Visual observation

For all nine combinations of binder type and curing conditions two specimens are tested with a moss growth promoting substance, and two specimens without the moss growth promoting substance. There was no significant difference between the specimens treated with a moss growth promoting substance and the specimens without this substance. In figure 7.13 specimens that didn't receive the moss growth promoting substance are shown after 3,5 months in the botanical garden. It can be seen that CEM III/B and CEM III/B + fly ash specimens that are air cured or cured with a curing compound have green staining on the surface. This indicates that a biofilm is formed, which can subsequently grow into moss. The other specimens did not show any green staining.

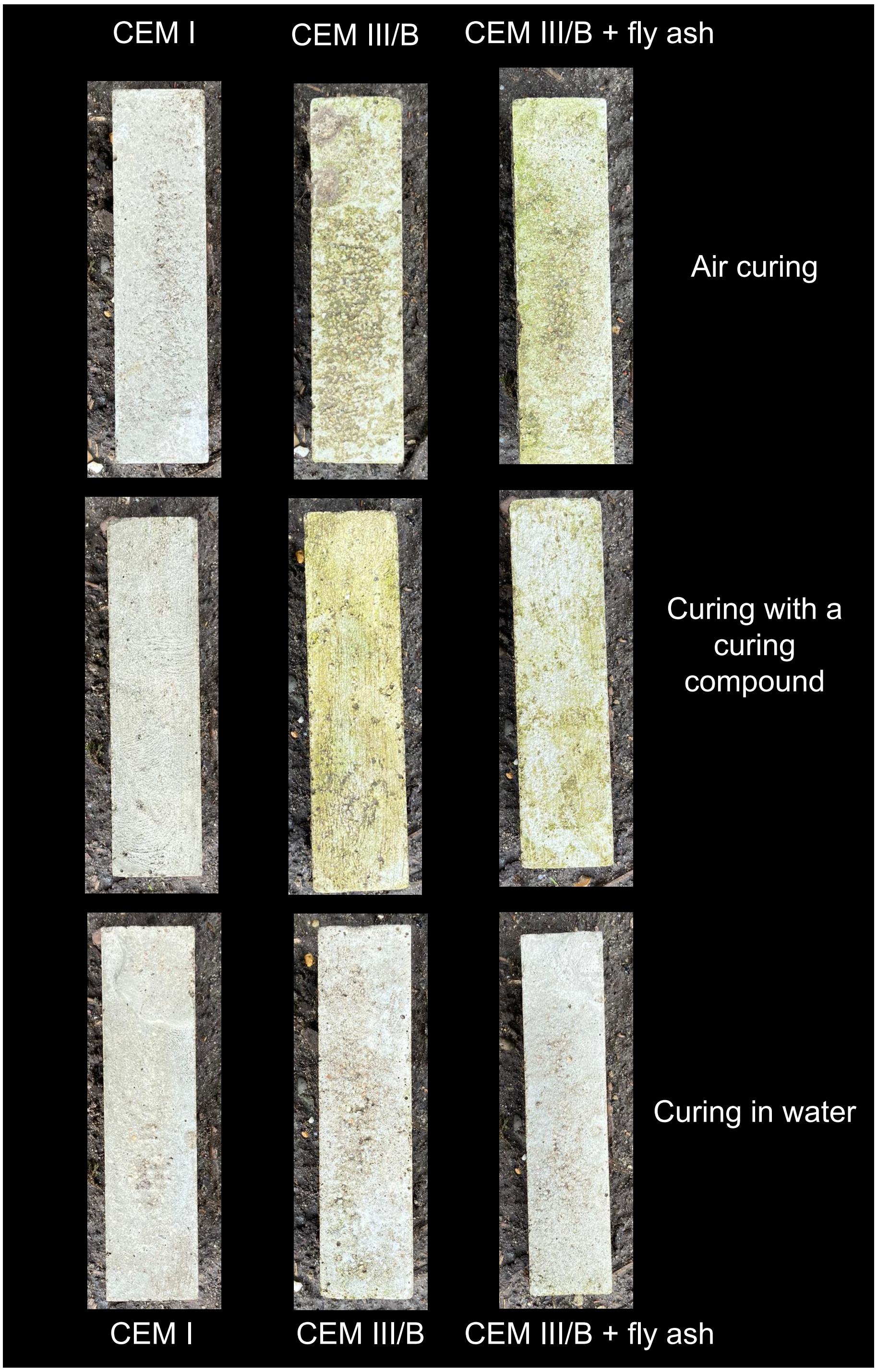


Figure 7.13: The specimens after 3,5 months in the botanical garden. The combination of a low-clinker content specimens that is air cured or cured with a curing compound gives the earliest biofilm growth, visualised as green staining on the specimens.

7.8 Moss experiments

In figure 7.14 the absorption (% of dry weight) and dry weight per square meter of moss concrete ($kg/m2$) of both moss species is given. It has been found that the absorption capacity of the moss species *Hypnum Cupressiforme* is more than twice of that of the moss species *Tortula Muralis*, respectively 1247 % and 615 % of the dry weight. The conversion of square meter to dry weight has shown that the *Tortula Muralis* has a dry weight of 1,185 kg per surface area m^2, while the *Hypnum Cupressiforme* has a dry weight of 0,531 kg per surface area (m^2).

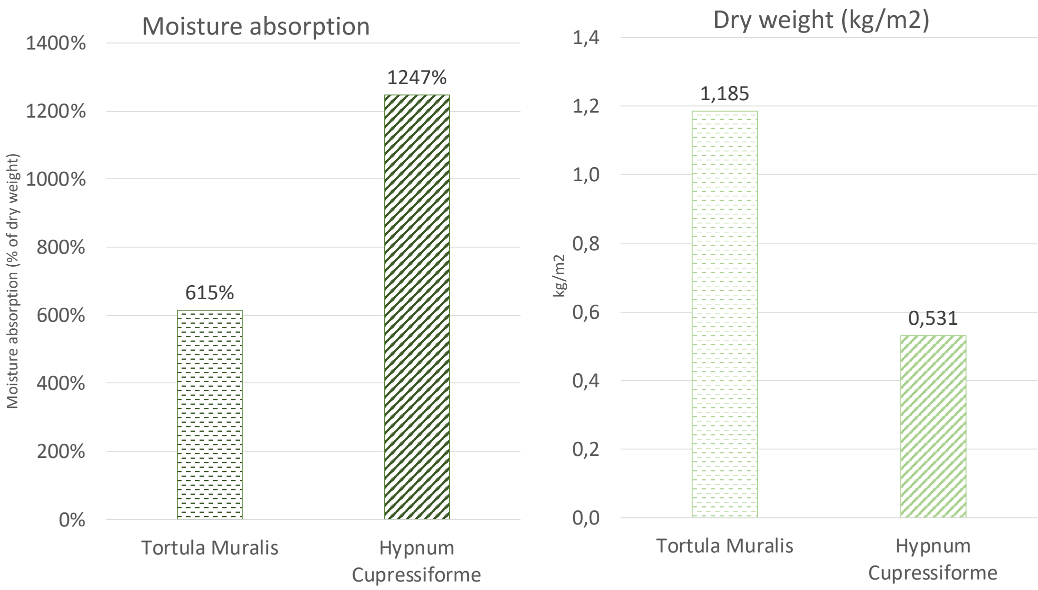


Figure 7.14: The water absorption of mosses as percentage of their dry weight and the dry weight per square meter (m^2) for the moss species Tortula Muralis and Hypnum Cupressiforme

In figure 7.15 the moisture loss of the moss samples over a 24 hour drying period is given. In appendix A.3 *Moss experiments* on page 117 the reaction speed of the evaporation of moisture is given, and a comparison is made between the moisture loss of both moss species and the mortar specimens. With the found results the CO_2 fixing rate and water absorption will be calculated in the case study on page 85.

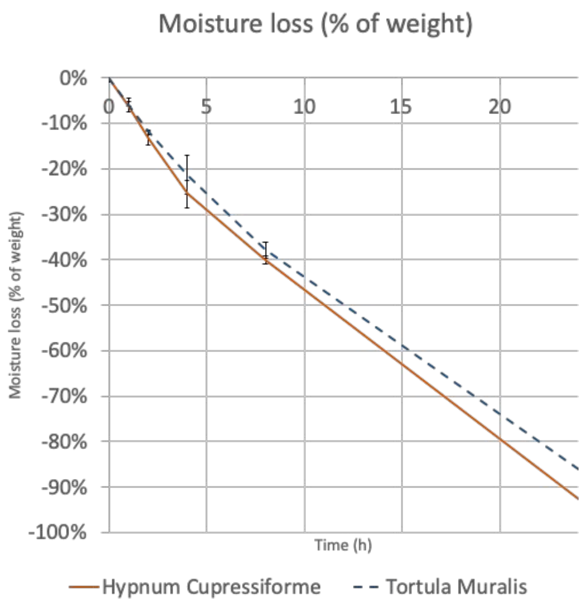


Figure 7.15: Moisture loss mosses

Chapter 8

Discussion

8.1 Discussion of results

8.1.1 Absorption tests and drying behaviour

The water absorption is a measure of the porosity and permeability of a specimen. The higher the water absorption, the more porous and permeable the specimen is. The relative large increase (98,56 %) in absorption on the surface of CEM III/B + fly ash samples when air cured instead of cured in water, visualised in figure 8.1, can be attributed to several things. Firstly, all specimens cured in water absorb less moisture. These samples have had a continuous supply of moisture available, which ensures an optimal hydration process. Due to these optimal curing conditions, a relative high amount of hydration products have been formed, as is explained in section 3.4 *Curing* on page 23 and can be confirmed by research [10][128]. The hydration products fill the empty pores, causing a lowering of the porosity, as is explained in section 3.5.1 *Porosity* and is visualised in figure 3.16 on page 27 [62].

When optimal cured, meaning in this research water cured, the water absorption of low-clinker content specimens (CEM III/B and CEM III/B + fly ash based) is relatively lower than the water absorption of high-clinker content specimens (CEM I based). This can be attributed, among others, to the fineness of the particles of the alternative binders present in the low-clinker content specimens and their hydration processes. As is explained in section 3.2.1 *Alternative binders* on page 16, both fly ash and blast furnace slag will contribute to a denser pore structure when properly cured, because both binders consist of very small, smooth spherical particles. Thereby, their hydration reactions take (partly) place in the pore solution, leading to a relatively lower porosity and permeability.

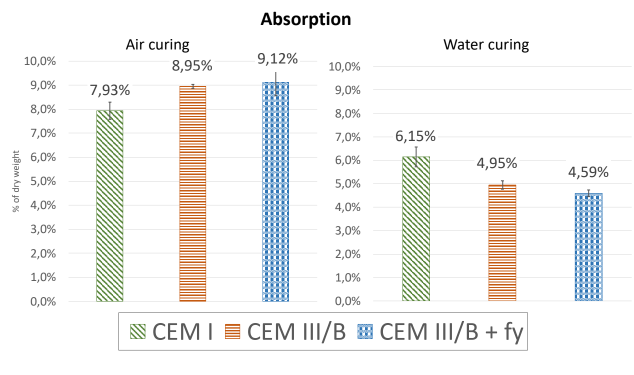


Figure 8.1: The water absorption of the surface of specimens that are air cured and water cured, and that consist of CEM I, CEM III/B and CEM III/B + fly ash. The surface of CEM III/B + fly ash specimens absorb most when water water cured, while least when air cured

When the low-clinker content specimens are compared, it was found that when the specimens are water cured CEM III/B + fly ash absorbs the least amount of water. This is caused by the additional amount of fly ash in these specimens, that replaces part of the binder as well as part of the bulking material, as is explained in section 6.2 *Mortar specimens* on page 51. When the CEM III/B + fly ash specimens are cured in water, this "extra" fly ash that replaces the sand will contribute in the hydration reaction, since the fly ash will not know which part has to act as binder and which part would have to act as bulking material. This leads to more hydration products in the CEM III/B + fly ash specimens that have cured in water compared to CEM III/B specimens, and therefore to the lowest water absorption.

Water can easily evaporate from specimens that have been air cured. This leads to less water available for the hydration process and can even causing the concrete to be dried out, as is described in section 3.4 *Curing* on page 23. When this happens the hydration reaction will cease, leaving the concrete with empty voids and little hydration products. Therefore air curing gives a higher porosity and permeability compared to water curing, which is shown as an increase in absorption. However, this increase in absorption differs per binder type, specimens that consist of CEM III/B and CEM III/B + fly ash absorb respectively 80,89 % and 98,56 % more water when air cured instead of water cured, in comparison to only 29,09% for CEM I. There are several reasons that explain this phenomenon:

1. A high amount of alternative binders Fly ash and blast furnace slag, that replace part of the clinker content in these mortar mixes, are activated by a latent-hydraulic and pozzolanic reaction, meaning that they need calcium hydroxide (CH) for their hydration process. This pozzolanic reaction occurs in two steps, and therefore takes more time than the hydraulic reaction of clinker, explained in section 3.3.2 *Hydration of alternative binders* on page 20. When clinker reacts with water calcium hydroxide is formed, which is than subsequently used by fly ash or blast furnace slag to create calcium silicate hydrates (CSH), the main building blocks of concrete, which is explained in section 3.3 *Concrete hydration* on page 18. Due to the evaporation of water the hydration process will cease in some parts of the specimen, and the low percentage of clinker might not be able to provide enough calcium hydroxide (CH) to properly start the second reaction stage of the hydration process of the alternative binders. This causes the fly ash and blast furnace slag particles to be unable to hydrate and therefore the low-clinker content specimens to be more porous and permeable.

2. Carbonation Previous research has found that carbonation, a process described in section 3.6.3 *Carbonation* on page 30, occurs most in samples that are air cured. Fattuhi et al. (1988) found that the carbonation rate of samples cured in water for 28 days was only 17 % of the carbonation rate of samples that had been cured in air [129]. The carbonation test executed in this research show that more carbonation can be seen for samples that have been air cured compared to cured in water, which can be observed in figure 7.7 on page 66. In case of samples that consist of CEM I, carbonation will cause the calcium hydroxide (CH) available in the pore solution to be transferred into calcium carbonate ($CaCO_3^{2+}$), which is a solid, thereby contributing to a relative more dense microstructure and therefore a lower water absorption when the samples haven't cured. This effect is supported by literature, and found in several experiments [130]. However, as described above, low-clinker concretes have less calcium hydroxide (CH) in their pore solution due to the pozzolanic reaction, which leads to the use of calcium silicate hydrates (CSH) in the carbonation reaction. This is the main building block of concrete and provides a solid structure, therefore their loss will lead to a lowering of the density of the microstructure and causes the samples to be more porous and permeable and to have a higher water absorption [130]. Research confirms that supplementary cementitious materials, such as fly ash and blast furnace slag are more vulnerable for carbonation [131].

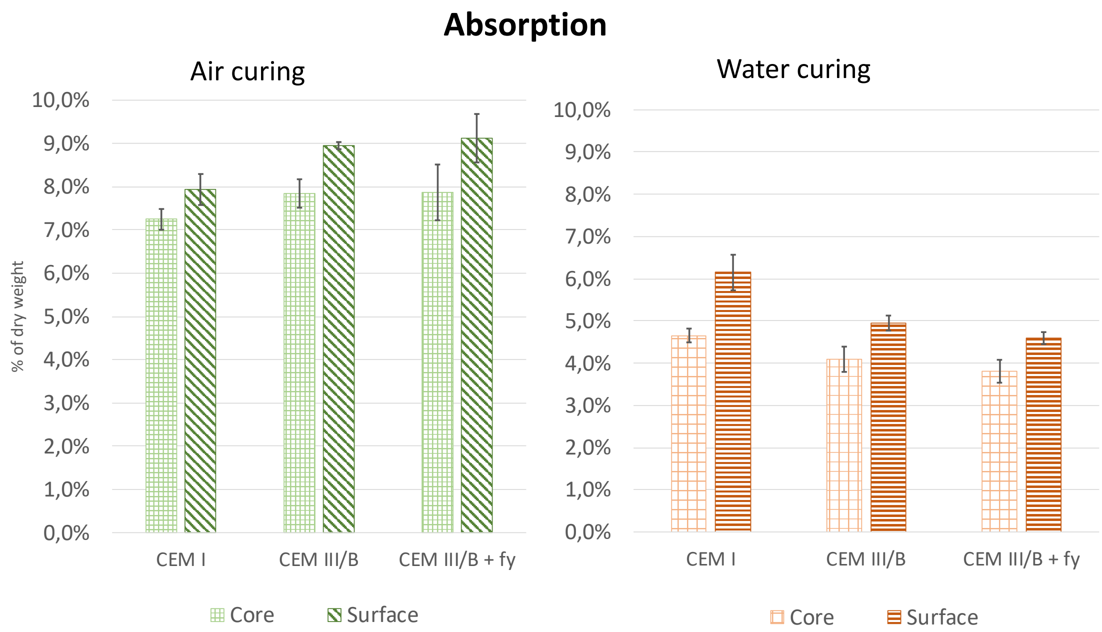


Figure 8.2: The water absorption of the core and surface of specimens that are air cured and water cured, and that consist of CEM I, CEM III/B and CEM III/B + fly ash. The core of each specimen absorbs less water than the surface.

Surface vs. core samples of curing conditions "air curing" and "water cured"

The core of specimens that are air cured or water cured absorbs consequently less water than the surface of these specimens, which is visualised in figure 8.2. This can be attributed to the fact that the surface is more imperfect than the core, causing it to be, among others, more porous and permeable. Several factors are causing this imperfections, such as the segregation at the surface due to bleeding, overworking the freshly casted mortar, carbonation, and the drying out of the cover zone due to the loss of water [120] [128]. Even if the curing conditions are optimal, still a difference can be observed between the surface and core concrete, which is the effect of the cover zone of concrete and is inevitable.

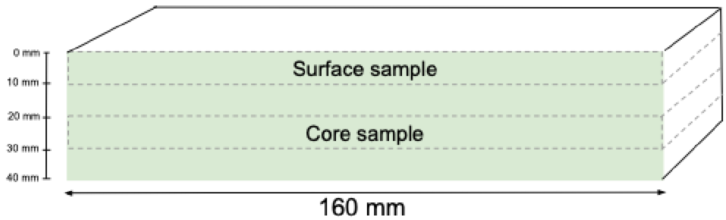


Figure 8.3: The location of the tested core and surface samples of each specimen, the outside of the prism has been in moulds *(Author's figure)*

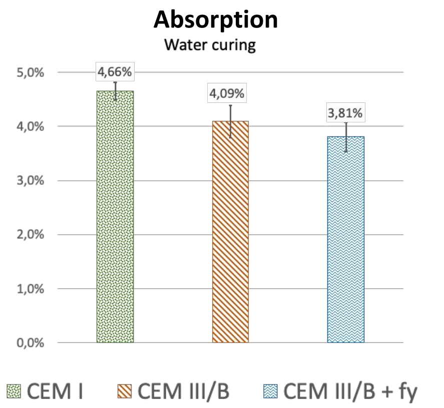


Figure 8.4: The water absorption of the core of specimens that have been cured in water and consist of CEM I, CEM III/B and CEM III/B + fly ash

Although the cores of most specimens absorbs relatively less water than the surface, a more homogeneous behaviour was expected between the water absorption of the cores of specimens that consist of the same binder type but differ in curing condition. The curing is assumed to have an effect on the first millimeters of the surface. Therefore, it surprising how much the cores are influenced by the curing conditions, visualised in figure 8.2. This might be attributed to the fact that the tested surface samples (first 10 *mm* from the surface) and the tested core samples (20-30 *mm* from the surface of the core samples) are laying too close too each other, visualised in figure 8.3. Research confirms this, as it is found that the properties of the first 40 *mm* beneath the surface can be influenced by the curing methods, from which the first 20 *mm* show the largest effect [120][130]. This effect might be re-enforced by the fact that the sides that surround the core samples have been in the moulds, as is visualised in figure 8.3. Together this might mean that we can't speak of a "core" samples here, and that the core samples behave more as a combination of a surface and a core sample, that follow the actual surface samples in a less extreme way. The cores of specimens that have been cured in water, which are shown in figure 8.4 give the most accurate representation of how the cores of each binder type would behave, irrespectively of the curing condition.

Curing with a curing compound

Specimens cured with a curing compound give different results than what would have been expected. The surface of low-clinker content specimens that are treated with a curing compound have a similar water absorption as the surface of specimens that are air cured, visualised in figure 8.5. Moreover, the core of low-clinker content specimens cured with a curing compound absorbs more water than the core of specimens that are air cured, visualised in figure 8.5. In contrary to the other curing conditions, the core and surface of specimens cured with a curing compound absorb a similar amount of moisture, due to the elevated absorption of the core of the specimens, visualised in figure 8.6. It was expected that a curing compound would lower the porosity and permeability, by preventing the evaporation of water and thereby enabling improved hydration. Although this effect has been obtained in other research [132], a different outcome is received in this research. The results of the drying behaviour tests indicate that the surface of low-clinker content specimens that are cured with a curing compound are more permeable and porous than the surface of low-clinker content specimens that are air cured. Therefore, it can be concluded that the curing compound didn't improve the hydration process of the specimens used in this research, and made it actually more porous and permeable in some cases. This is the opposite of what is supposed to happen, and questions the use of a curing compound altogether. Further research should be conducted to understand the reactions happened in this research between the low-clinker content specimens and the curing compound, and their effect on the hydration process.

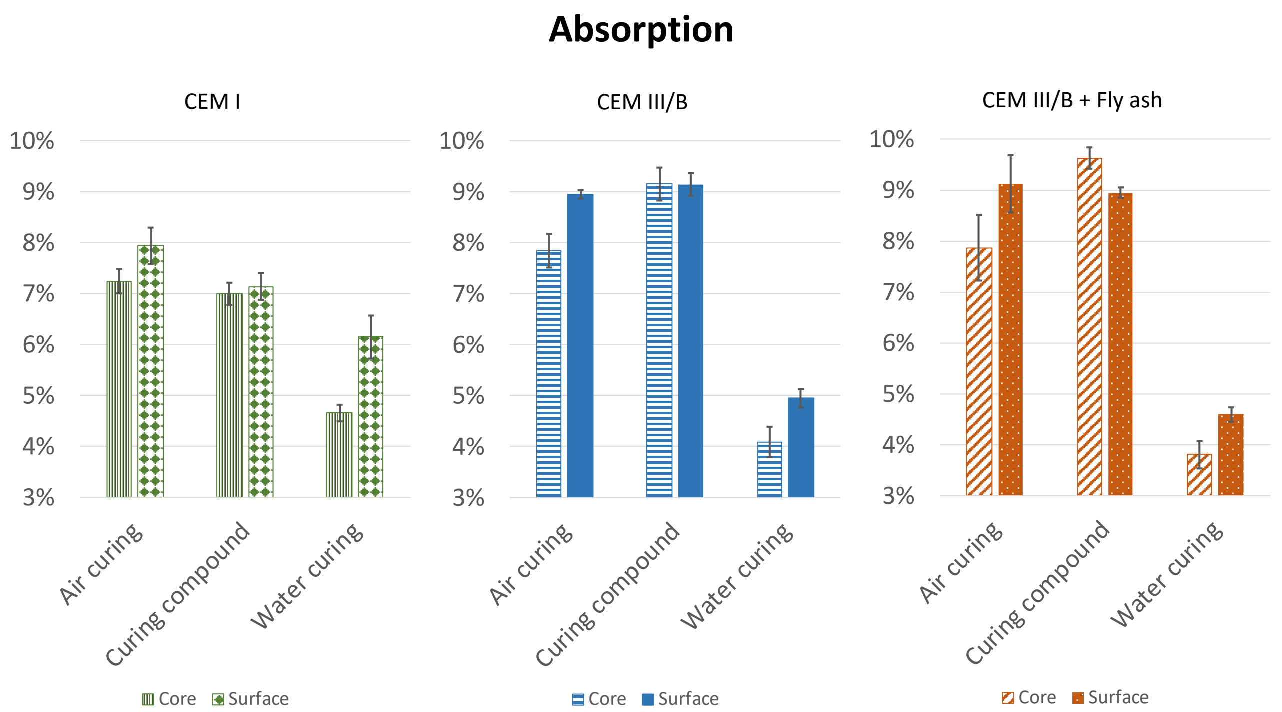


Figure 8.5: The water absorption of the core and surface of specimens that consist of CEM I, CEM III/B and CEM III/B + fly ash, and are air cured, cured with a curing compound, and water cured. The cores of low-clinker content specimens cured with a curing compound absorb more water than the cores of air cured specimens. The surface of of low-clinker content specimens cured with a curing compound absorb a similar quantity of water as the surface of air cured specimens.

Surana et al. (2017) found that the rate of strength gain when a curing compound is used reduces drastically after three days, wondering if there is not enough water available for the hydration process after three days [120]. This might mean that a curing compound will have an effect only during the first couple of days. This explains why the curing compound does have an effect on the high-clinker content specimens, these samples have a faster hydration process than the low-clinker content samples and therefore the curing compound can work advantageous.

When looking back at the execution of the experiment, one may wonder if applying the curing compound at the moment that the surface water has disappeared from the specimens may not be the optimal application, although the manufacturers recommend this. This has been investigated by Wang et al. (1994), that confirm that the effectiveness of a curing compound is largely depending on the time of application [133]. The later a curing compound is applied on the surface, the smaller the positive effect on the performance of the concrete is, meaning that if a curing compound is applied too late on site, the benefits will be significantly eroded. This explains why little difference is found between specimens cured with a curing compound and specimens that didn't receive any curing. For optimal performance of the curing compound, Wang et al. (1994) recommend to apply the curing compound immediately after the finishing of the concrete surface [133], however this might interfere with the hydration process in other ways.

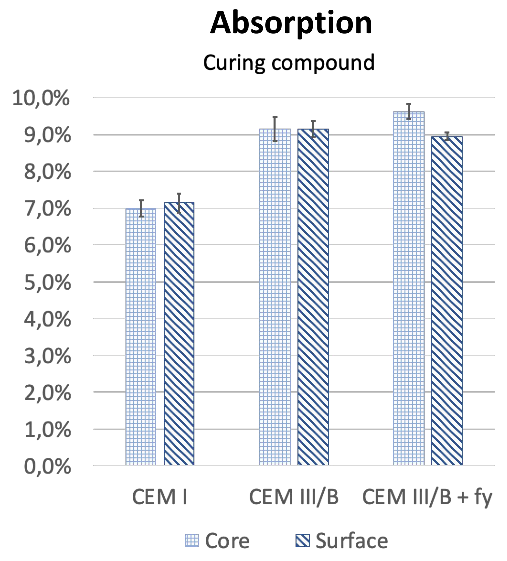


Figure 8.6: The water absorption of the core and surface of specimens that have been cured with a curing compound. The absorbed quantity of the core of the specimens is similar or even higher than the absorbed quantity of the surface.

8.1.2 Epoxy impregnation

The results of the epoxy impregnation indicate that the specimens that are air cured are more porous and permeable than water cured specimens. The results of the epoxy impregnation test are in line with the found results of the absorption and drying test. From the results of the conducted absorption tests it seems that there is little difference in absorption between the surface of specimens cured in air or cured with a curing compound. However, this difference is seen more clearly in the results of the epoxy impregnation test. The low-clinker content specimens cured with a curing compound have more epoxy penetrated to the core of the samples than the air cured specimens. This phenomenon is not seen in CEM I specimens, which is in line with the results of the absorption and drying tests. However, it must be noted that there is only one epoxy impregnation test executed for each combination of binder type and curing condition. To give a more substantiated conclusion, the epoxy impregnation test should be repeated several times. The curing compound does have an effect for the high-clinker content samples, which can be attributed to the faster reaction of these samples. The results of the epoxy impregnation test visualised the effect that is observed in the results of the absorption test and drying test, namely that the curing compound actually makes low-clinker content samples more porous and permeable. This might be due to an unforeseen reaction that occurs between the curing compound and the specimen. However, this is only speculation, more research with several curing compounds should be executed to test this and draw accurate conclusions on the witnessed process.

8.1.3 Carbonation

In the results of the carbonation tests it can be seen that specimens cured in water show less carbonation than specimens cured in air, which confirms the expected behaviour. As is explained in the section 8.1.1 *Absorption and drying behaviour* on page 73, this effect is also confirmed in literature. Fattuhi et al. (1988) found that the carbonation rate of samples cured in water for 28 days was only 17 % of the carbonation rate of samples that had been cured in air [129]. It can be seen that for each curing condition CEM I specimens show the least amount of carbonation, which can be attributed to the hydration products that are formed in during the hydration of clinker. In the results of the carbonation test it is visualised that the low-clinker content specimens have carbonated more when a curing compound is being used. However, it must be noted that there is only one carbonation test executed for each combination of binder type and curing condition. To give a more substantiated conclusion, the carbonation experiments should be repeated several times.

8.1.4 MIP

In the results of the three successful Mercury Intrusion Porosimetry tests, executed on air cured specimens, two peaks can be found. The peak around 0,01 μm is what can be expected when a sample with a high content of alternative binders is analysed, since this peak represents the gel pores. Due to the hydration process of fly ash and blast furnace slag, both explained in section 3.3.2 *Hydration of alternative binders* on page 20, more gel pores are formed compared to the clinker hydration. A peak between 0,1 - 1 μm was expected for high-clinker content samples, since this represents the increased amount of capillary voids that exist in these specimens, as is described in section 3.3 *Clinker hydration* on page 18. However, this peak is not found, instead a peak is seen for the low-clinker content specimens. This unexpected result raises the question if the low-clinker mixes have hydrated so little that the amount of capillary pores is still elevated, while the CEM I sample had initially an ever higher peak here, lowered due to hydration process. However, this cannot be concluded from the MIP experiments that have been executed for this thesis. To find out what causes the lack of a peak here for CEM I samples, and what creates the peak for low-clinker mixes, more MIP experiments have to be executed.

8.1.5 Buffer capacity test

The buffer capacity towards alkalinity means the ability to neutralize incoming acid without compromising on the pH level, as is explained in section 6.3.4 *Buffer capacity test* on page 56. In the pore solution the incoming acid will react with the dissolved calcium hydroxide (CH), as is illustrated in reaction 8.1. Therefore, the amount of calcium hydroxide available is of great influence on the buffer capacity towards alkalinity. The pH value of the solution indicates the amount of calcium hydroxide that is present.

$$H_3O^+ + OH^- \longrightarrow 2H_2O \tag{8.1}$$

The CEM I specimens have the highest pH at the start of the experiment. This is what was expected, since the hydration process of clinker produces calcium hydroxide, and CEM I cement consists for 95-100 % of clinker [6]. In the low-clinker content specimens there is some clinker present that produces calcium hydroxide, but this will react in a second reaction with the alternative binders to create calcium silicate hydrates (CSH), explained in section 3.3.2 *Hydration of alternative binders* on page 20. Therefore, low-clinker content mixes will have a relatively low quantity of calcium hydroxide available in their pore solution, as is confirmed in the results by a relatively lower pH at the start of the experiments.

If the effect of the curing condition is compared for each binder type, it can be seen that the pH at the start of the experiment is highest for specimens cured in water. This can be attributed to several reasons. Firstly, calcium hydroxide is a hydration product and optimal curing (water curing) will result in the highest amount of hydration products being produced [62]. Secondly, the carbonation reaction will use calcium hydroxide if available, as is described above and in section 3.6.3 *Carbonation* on page 30. The carbonation rate of samples cured in water is only 17% of that of samples cured in air [129]. This will result in more calcium hydroxide available in the pore solution of samples that have been water cured, and therefore a higher pH.

During the experiments, samples that consist of CEM I are able to buffer relatively most acid, especially when cured in water. This is in line with what is expected, since these samples have most calcium hydroxide available as is described above. The low-clinker content samples show an elevated buffer capacity towards alkalinity when the samples are cured in water instead of air cured, but this is relatively a small increase compared to the increase in acid added to the CEM I specimens that are cured in water instead of in the air. Even though most hydration products have been formed when CEM III/B samples and CEM III/B + fly ash samples are cured in water, the produced calcium hydroxide particles will react in the second hydration reaction to create calcium silicate hydrates, as is described above and in section 3.3.2 *Hydration of alternative binders* on page 20. On the other hand, when low-clinker

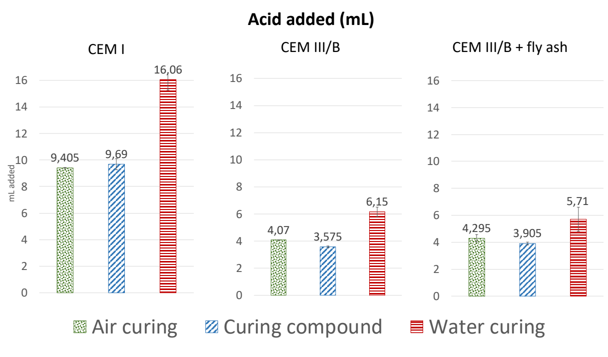


Figure 8.7: Total amount of acid added during the experiments

content specimens are air cured, there will be little calcium hydroxide present in the pore solution due to carbonation and the fact that there are less hydration products being formed in the first place.

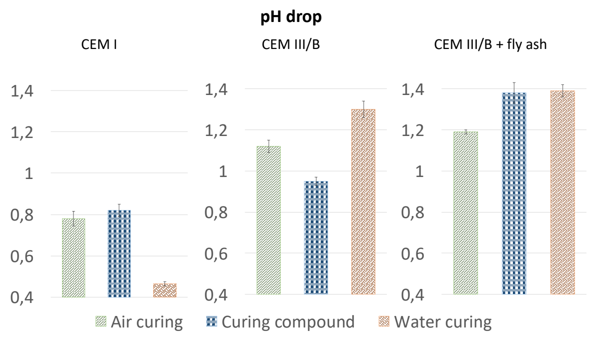


Figure 8.8: The pH drop at the end of the experiment

The pH_{drop} is a measure of the buffer capacity towards alkalinity that is left in the samples at the end of the experiment. A small pH_{drop} shows that there is still relatively a lot of calcium hydroxide left that can react with the incoming acid. As is expected, CEM I samples show the lowest pH_{drop}, especially when cured in water. This shows that CEM I samples that have been properly cured have relatively the highest buffer capacity towards alkalinity, since the samples can take up almost three times as much acid as the samples of CEM III/B and CEM III/B + fly ash and still have most buffer capacity left at the end of the experiment. The low-clinker content samples show that even though some specimens have cured in water, at the end of the experiment there is relatively little buffer capacity left in all of the specimens. The low-clinker content specimens that are air cured show a smaller pH drop than the specimens that have been cured in water, this can be attributed to the slightly higher amount of acid added to the water cured samples, leading to the loss of buffer capacity.

The curing methods *air curing* and *curing with a curing compound* show very similar amounts of acid added and reaction kinetics during the experiment. The samples used in the buffer capacity tests are surface samples, and therefore these results are in line with the found results for the absorption tests. All of the tests that have been performed conclude the same outcome, that curing with a curing compound doesn't give an improved hydration.

Research on the influence of the cement type towards the resistance of acid has shown different outcomes in their experiments. De Belie et al (1996) concluded in their research that Ordinary Portland Cement (CEM I) is more vulnerable for an acid attack than CEM III/B based cement[134]. However, in their research the concrete samples were exposed to four cycles of a strong acid attack (pH = 2/3) and after each phase the surface was brushed to detach unstable concrete [134]. The amount of material that was lost during brushing showed the resistance against acid attack, in which CEM III/B came best out of the test, and CEM I as worst. However, it must be noted that all specimens first received excellent curing conditions (28 days of RH 90%/20 °C), leading to a very dense pore structure of low-clinker content samples compared to CEM I samples. Testing in such a strong acidic environment (pH = 2/3) will quickly lead to a lowering in the amount of calcium hydroxide to buffer the incoming acid. Therefore the advantage that CEM I has over low-clinker mixes when buffering incoming acid is quickly erased, and is not shown in this kind of experiment. In contrary, now the microstructure of the concrete will determine the amount of acid that will enter the samples, leading to a better performance of concrete with a dense microstructure. Since the optimal curing of low-clinker content mixes leads to a denser microstructure, as has been found in this research, these mixes have the best outcome in the experiments executed by De Belie et al. (1996). This leads to wondering what would happen if this experiment would be repeated with specimens that are air cured and cured with a curing compound.

The type of experimental program that is chosen to test the resistance of a sample against an acid attack is of great influence. The outcome must be analysed carefully with regard to the used cement type and curing conditions. For an highly acidic (pH=2) environment, a dense microstructure is most important. When optimal cured, concrete with a high slag (and fly ash) replacement performs best. However, when analyzing the effect that "slowly" incoming acid has in an alkaline environment, and thus looking at the buffering capacity towards alkalinity, CEM I based samples perform best. This shows that it is important to realise the environment in which the concrete will be placed, and the effects that the kind of curing and the cement type have. For this research the interest is to grow mosses on concrete, in normal outdoor conditions and not in a heavily acidic and aggressive environment. Therefore, the ability to buffer incoming acid will be of great importance in deciding the relative best concrete mix based on this research outcome. The results of the buffer capacity test performed in this research show that the use of low-clinker mixes will lead to the lowest buffering capacity towards alkalinity. This in combination with air curing will give a porous and permeable sample, that will allow acid to easily enter the surface.

8.2 Summary

In figure 8.9 a summary of the discussion is visualised for low clinker content mix that have been insufficiently cured and that are cured in water. The discussed effect of the curing conditions on a high clinker content mix have been shown in figure 8.10.

Figure 8.9: The effect of curing on a low-clinker concrete mix *(Author's figure)*

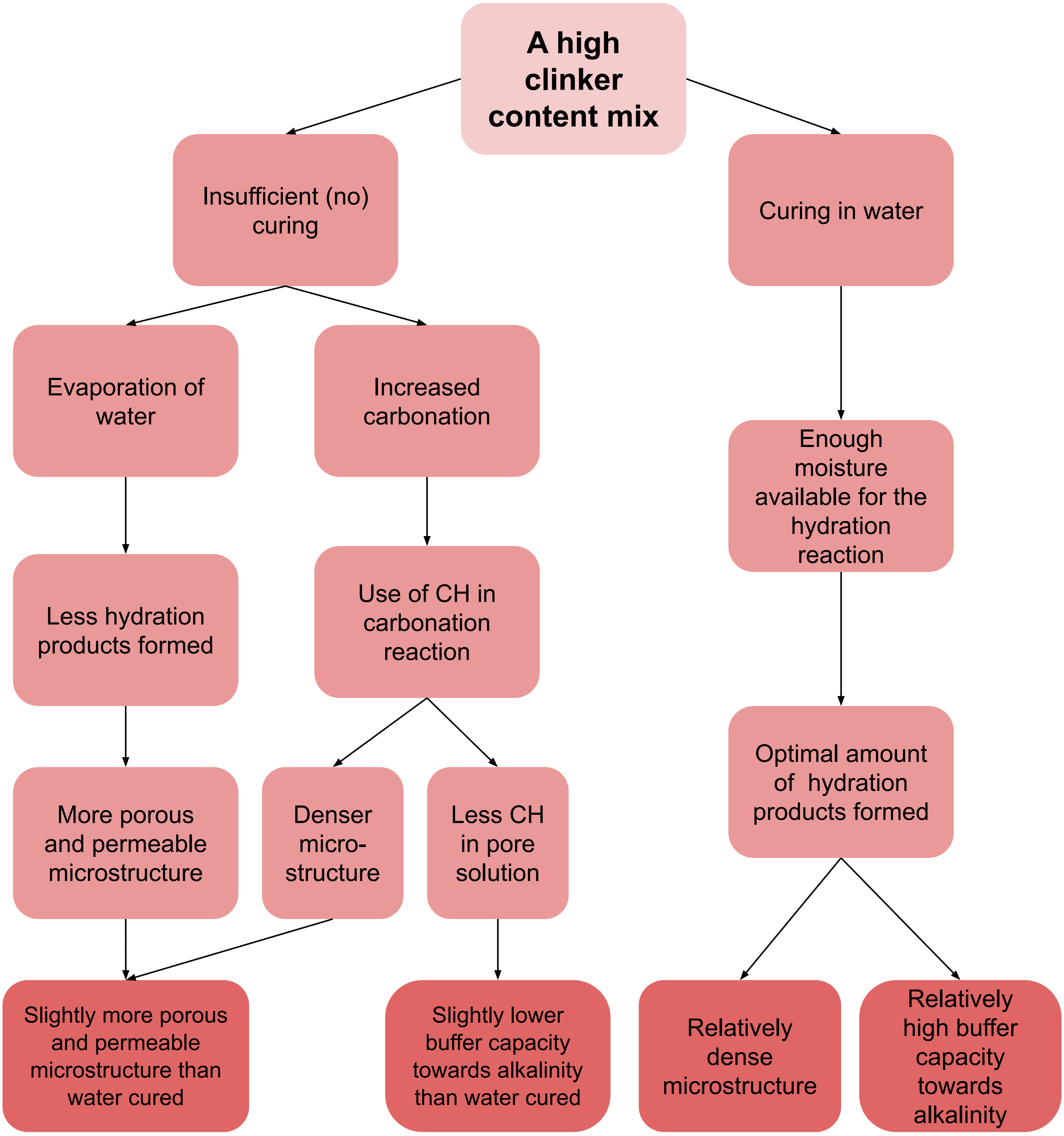


Figure 8.10: The effect of curing on a high-clinker concrete mix *(Author's figure)*

8.3 Answering hypothesis I

The objective of the experiments was to answer the following hypothesis:

Hypothesis I: A low-clinker content concrete (CEM III/B based) is more vulnerable for insufficient curing (air curing or paraffin curing) than concrete with a high-clinker content (CEM I), leading to a relatively more porous and permeable concrete cover zone.

The results of the conducted experiments confirm the first hypothesis. It can be concluded from this research that a low-clinker content concrete is definitely more vulnerable for insufficient curing than concrete with a high-clinker content. The result of insufficient curing instead of water curing of a low-clinker content specimen leads to an increase of 98,56 % of the water absorption, while for a high-clinker content specimen this increase is only 29,09 %. The higher the degree of water absorption, the more porous and permeable a concrete is. The results from the carbonation test and epoxy impregnation test confirm the result of the absorption and drying test. Thereby it has been found that curing with a curing compound, in this case paraffin curing that is applied according to the standards of the manufacturer, doesn't give an improved hydration. Paraffin curing can even be marked as insufficient curing according to the results found in this research.

Insufficient curing will lead to increased carbonation, that has huge effects on the porosity and permeability of specimens with a high amount of alternative binder and a low amount of clinker. These specimens do not have enough calcium hydroxide available to make the solution more alkaline, thereby preventing the second reaction of the hydration process that uses calcium hydroxide to create calcium silicate hydrates. This will cause the samples to be more porous and permeable. The findings in this thesis contradict findings from other research, since among others Saricimen et al. (1995) concluded from their research that the use of alternative binders in concrete leads to technological and economical benefits because of the lower permeability than "plain" (CEM I) concrete, irrespectively of the curing procedure [128]. This statement does not hold for this research, where the curing conditions certainly have an effect on the permeability of low-clinker content samples, and insufficient curing will cause these samples to be more permeable than CEM I specimens.

8.4 Answering hypothesis II

The objective of this buffer capacity towards alkalinity test was to test the following hypothesis:

Hypothesis II: A low-clinker content concrete (CEM III/B based) will have a lower buffering capacity towards alkalinity than concrete with a higher clinker content (CEM I). A low buffer capacity leads to a lowering of the durability, since there will be more corrosion, the carbonation will lead to more porosity, and the concrete will be more bioreceptive

From the results found in this research it can be concluded that a low-clinker content specimen has the lowest buffer capacity. It seems from the found results that the curing method used has a relatively small influence on the buffer capacity towards alkalinity for low-clinker content specimens. However, in practice the acid must first enter the concrete before the internal reactions occur. Therefore it is important to realize that the microstructure of the sample is also of influence. Even though little difference is found between the buffer capacity towards alkalinity of low-clinker specimens that have been air cured or water cured, their internal microstructure differs significantly. This is confirmed by the absorption tests, epoxy impregnation and carbonation test. Air curing will lead to a relatively more porous and permeable microstructure, which makes it easier for incoming acid to enter the concrete cover zone. The combination of a low-clinker concrete together with insufficient curing will lead to the lowest buffering capacity and easiest acid ingress.

Part III

Case study

Chapter 9

Current situation

9.1 Current impact

With the results that have been found for the executed moss experiments, the current impact that mosses have can be calculated. With the water absorption rate and the surface to dry weight conversion the CO_2 fixing rate and needed evaporation for cooling can be calculated.

CO_2 fixing rate

In chapter 4 *Moss concrete* several positive effects of moss growth on concrete have been found. One of the properties of moss is that it can take up $CO2$, which is explained in section 4.1 *Why moss concrete?* on page 33. In this thesis the potential of the $CO2$ uptake by mosses is quantified

In literature it has been found that the moss specie *Tortula Muralis* absorbs 96,8 μg CO_2 per hour per gram dry weight of moss. In this research it has been assumed that the specie *Hypnum Cupressiforme* absorbs the same amount of CO_2. Therefor, when the moss concrete area (m^2) is known, the dry weight can be calculated, which will give the amount of CO_2 in (g/hour) that has been fixated by the mosses. Aulia et al. (2018) use a conversion of 360 active hours each month for vegetation [135]. It is assumed in this research that the mosses are also active for 360 hours a month.

Method

From the experiments the known surface to dry weight conversion has been calculated. With the following formula the CO_2 capture in $g/hour$ per square meter of moss concrete can be calculated.

$$CO_2\ capture\ (g/hour/m^2) = \varphi = \epsilon \times \kappa \tag{9.1}$$

$$CO_2\ capture\ (kg/year/m^2) = \varsigma = \frac{\varphi}{1000} \times h \times m \tag{9.2}$$

φ = the CO_2 capture in $g/hour$ per m^2 of moss concrete
ς = the CO_2 capture in $kg/year$ per m^2 of moss concrete
ϵ = dry weight to surface ratio (kg/m^2), this has been found to be 0,531 kg/m^2 for the specie Hypnum Cupressiforme, and 1,185 kg/m^2 for the specie Tortula Muralis
κ = the capture of CO_2 per dry gram of moss, this has been found to be 96,8 μg of CO_2 per hour per dry g of moss for the specie Tortula Muralis. In this research it is assumed that the species Hypnum Cupressiforme absorbs the same amount of CO_2 per hour per dry g of moss
h = hours in a month that the moss is active, assumed to be 360 $hours$
m = months in a year that the moss is active, assumed to be 12 $months$

$$\varphi_{Hypnum} = 0,531 * 10^3 \times 96,8 * 10^-6 = 0,0514\ g/hour/m^2\ , \quad \varsigma_{Hypnum} = \frac{0,0514}{1000} \times 360 \times 12 = 0,222 kg/year/m^2 \tag{9.3}$$

$$\varphi_{Tortula} = 1,185 * 10^3 \times 96,8 * 10^-6 = 0,1147\ g/hour/m^2\ , \quad \varsigma_{Tortula} = \frac{0,1147}{1000} \times 360 \times 12 = 0,496 kg/year/m^2 \tag{9.4}$$

When the surface area and the degree of covering by mosses is known, the surface area that is covered by mosses can be calculated.

$$Moss\ area\ (m^2) = \lambda = Astr \times Ccover \tag{9.5}$$

$$Dry\ weight\ of\ moss\ (kg) = \beta = \epsilon \times \lambda \tag{9.6}$$

A_{str} = total area of the structure (m^2),
$Ccover$ = degree of covering (%),
λ = area of the structure that is covered with moss (m^2)
β = dry weight of mosses on the surface of the structure (kg)

$$CO_2\ capture\ total\ structure\ (g/hour) = \phi = \varphi \times \lambda \tag{9.7}$$

$$CO_2\ capture\ total\ structure\ (kg/year) = \sigma = \frac{\phi}{1000} \times h \times d \tag{9.8}$$

ϕ = CO_2 capture of the total structure per hour (g/hour),
σ = CO_2 capture of the total structure per year (kg/year)

Water absorption & evaporation

Moss concrete can absorb a large amount of water, as is explained in section 4.1 *Why moss concrete?* on page 33. This is already positive nowadays, but will be even more important because of the changing climate. It is expected that in the future heavy rainfall will be followed by long periods of drought, in which the presence of moss concrete will lead to significant improvements in the environment. This is because mosses are able to absorb an abundance of water during heavy rainfall, thereby preventing urban flooding, after which mosses can evaporate this kept water during dry spells. This evaporation will cool the air surrounding the moss concrete.

The necessary water evaporation to cool the air around the moss concrete structure can be calculated. It is assumed that the air 3 meter from the moss concrete surface has to be cooled.

$$Water\ uptake\ of\ structure\ (kg) = \xi = \alpha \times \beta \tag{9.9}$$

ξ = water uptake of the mosses on the structure (kg)
α = water absorption per moss species (%)
β = dry weight of mosses on the surface of the structure (kg).

$$Air\ volume\ (m^3) = \tau = Astr \times H \tag{9.10}$$

$$Air\ mass\ (kg) = m = \tau \times \rho \tag{9.11}$$

τ = air volume that is cooled (m^3)
A_{str} = area of the structure (m^2)
H = height of the air that is cooled (m), assumed to be 3 meter
m = weight of the air that is cooled (kg)
ρ = air density (kg/m^3), for 15 °C this is 1,2225 kg/m^3[136]

$$Energy\ needed\ (kJ) = P = m \times c \times \Delta T \tag{9.12}$$

ΔT = decrease in temperature of the air mass around the structure (K), it is chosen to realize a lowering of the air temperature of 5 K
P = energy that is needed for a decrease of ΔT in temperature of air mass m
c = specific heat capacity of air ($kJ/(kg * K)$) ,this is 1,00 $kJ/(kg * K)$ for air of 15 °C [137]

$$Water\ that\ needs\ to\ evaporate\ (kg) = W = \frac{P}{\Delta Hvap} \tag{9.13}$$

$$Average\ evaporation\ (kg/day) = E = M * A_{str} \tag{9.14}$$

$$Percentage\ of\ available\ water\ that\ needs\ to\ evaporate\ (\%) = \frac{W}{\xi} \tag{9.15}$$

ΔH_{vap} = Enthalpy of vaporization, this is the energy that is needed to evaporate the water (kJ/kg) which is 2465,4 kJ/kg for water at 15 °C) [138]
W = amount of water that needs to evaporate to provide energy for the decrease in temperature of ΔT of the air
M=average daily evaporation of water in the Netherlands, the yearly average is 595 mm^3/mm^2 in Delft, which can be converted to $1,627\ kg/m^2$ per day [139]
E=average daily evaporation of the structure in kg

9.2 Present applications

With the methods explained above the CO_2 fixing rate and needed water evaporation can be calculated. In this research eleven case studies have been chosen to analyse the CO_2 fixing rate and needed evaporation for a 5 °C cooling around the moss concrete surface. In order to compare the found values, the CO_2 emission for several transport types are given below in table 9.1. In table 9.2 the average annual CO_2 emission per citizen is given for several countries. To compare mosses to other types of vegetation, the CO_2 fixation of several vegetation types is given in table 9.3.

CO_2 emission	
Diesel car	emits 1 kg of CO_2 per 5,882 km [140]
Petrol car	emits 1 kg of CO_2 per 5,263 km [140]
Train - long distance	emits 1 kg of CO_2 per 100 km [140]
Train - local	emits 1 kg of CO_2 per 25 km [140]
Bus	emits 1 kg of CO_2 per 9,091 km [140]
Tram	emits 1 kg of CO_2 per 25 km [140]
Subway	emits 1 kg of CO_2 per 33,33 km [140]

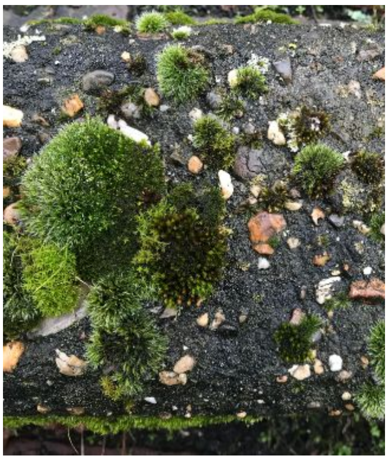
Table 9.1: Emission of CO_2 per transport type

Average annual CO_2 emission per citizen	
the Netherlands	emits 15.790 kg of CO_2 per year [141]
the USA	emits 20.000 kg of CO_2 per year [142]
Average homeless person of the US	emits 8.500 kg of CO_2 per year [142]
the UK	emits 9.660 kg of CO_2 per year [143]
Luxembourg	emits 26.280 kg of CO_2 per year [141]
the United Arab Emirates	emits 35.050 kg of CO_2 per year [141]
Indonesia	emits 1.210 kg of CO_2 per year [141]

Table 9.2: Average annual emission of CO_2 per citizen

CO_2 fixation	
Moss specie *Hypnum Cupressiforme*	fixates 0,222 kg of CO_2 per $m2$ per year
Moss specie *Tortula Muralis*	fixates 0,469 kg of CO_2 per $m2$ per year
Prairie	fixates 1,184 kg of CO_2 per $m2$ per year [135]
Average bush	fixates 5,426 kg of CO_2 per $m2$ per year [135]
Native broad-leaf tree	fixates 10 kg of CO_2 per year [140]
Average tree	fixates 56,125 kg of CO_2 per $m2$ per year [135]

Table 9.3: Fixation of CO_2 per vegetation type



Case 1

What:	A small wall
Where:	Smidswater, The Hague
Age:	Unknown (+10 years)
Material:	Asphalt
Surface:	8,25 m^2
Covering:	30%
Moss surface:	2,475 m^2,
Moss type:	Tortula muralis
Dry weight:	2,934 kg
Water uptake:	18,074 liter
CO2 uptake:	1,227 kg/year
CO2 equivalent:	Driving from Delft to Rotterdam with a Diesel car

0,34 % evaporation will give a lowering of 5 °C air temperature 3m around the wall


Case 2

What: Walkway for pedestrians
Where: Station Delft Campus
Age: Unknown (+10 years)
Material: Concrete
Surface: 150 m^2
Covering: 2 %
Moss surface: 3 m^2,
Moss type: Tortula Muralis
Dry weight: 3,556 kg
Water uptake: 21,82 liter
CO2 uptake: 1,478 kg/year
CO2 equivalent: From Rotterdam to Brussels and back by long distance train

5,11 % evaporation will give a lowering of 5 °C air temperature 3m around the walkway


Case 3

What: A small wall
Where: Karel Doormanlaan, Voorschoten
Material: Bricks and mortar
Age: Unknown (+10 years)
Surface: 8 m^2
Covering: 70%
Moss surface: 5,6 m^2
Moss type: Hypnum
Dry weight 2,971 kg
Water uptake: 36,993 liter
CO2 uptake: 1,243 kg/year
CO2 equivalent: From Delft to Amsterdam with a sprinter (local train)

0,16 % evaporation will give a lowering of 5 °C air temperature 3m around the walkway


Case 4

What: A bunker from WWII
Where: Staelduinse Bos
Material: Concrete
Age: 85 years
Surface: 52,5 m^2
Covering: 35%
Moss surface: 18,375 m^2
Moss type: - (Tortula muralis used)
Dry weight 21,780 kg
Water uptake: 133,65 liter
CO2 uptake: 9,108 kg/year
CO2 equivalent: From Delft to Amersfoort with a petrol car

0,29 % evaporation will give a lowering of 5 °C air temperature 3m around the walkway

Case 5

What: A statue
Where: Voorschoten
Material: Unknown
Age: Unknown
Surface: 2 m^2
Covering: 65%
Moss surface: 1,3 m^2
Moss type: Unknown (Hypnum used)
Dry weight 0,690 kg
Water uptake: 8,588 liter
CO2 uptake: 0,288 kg/year
CO2 equivalent: From North Amsterdam to South Amsterdam with the subway

0,17 % evaporation will give a lowering of 5 °C air temperature 3m around the walkway

Case 6

What: A roof
Where: Coolsingel, Rotterdam
Material: Unknown
Age: Unknown
Surface: 3 m^2
Covering: 70%
Moss surface: 2,1 m^2
Moss type: Unknown (Hypnum used)
Dry weight 1,114 kg
Water uptake: 13,872 liter
CO2 uptake: 0,466 kg/year
CO2 equivalent: From Delft to The Hague by bus

0,16 % evaporation will give a lowering of 5 °C air temperature 3m around the walkway

Case 7

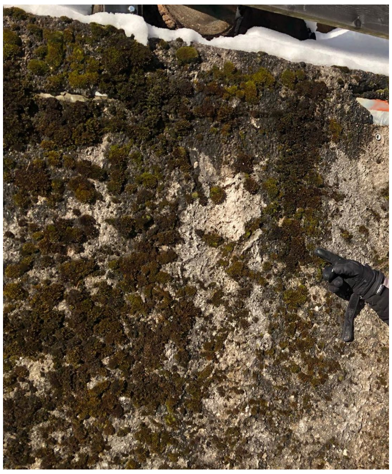
What: A wall
Where: Hooikade, Delft
Material: Bricks and mortar
Age: 2 years
Surface: 3,2 m^2
Covering: 30%
Moss surface: 0,96 m^2
Moss type: Tortula Muralis
Dry weight 1,138 kg
Water uptake: 6,983 liter
CO2 uptake: 0,476 kg/year
CO2 equivalent: Driving from Voorschoten to Wassenaar by diesel car

0,34 % evaporation will give a lowering of 5 °C air temperature 3m around the walkway

Case 8

What: A bank wall
Where: Hoekeindseweg (96), Bleiswijk
Material: Concrete
Age: Unknown (+10 years)
Surface: 18 m^2
Covering: 60%
Moss surface: 10,8 m^2
Moss type: Tortula Muralis
Dry weight 12,801 kg
Water uptake: 78,553 liter
CO_2 uptake: 5,353 kg/year
CO_2 equivalent: From Amsterdam to Paris by long distance train

0,17 % evaporation will give a lowering of 5 °C air temperature 3m around the walkway



Case 9

What: Wall
Where: Canazei, Italy
Material: Concrete
Age: Unknown (+10 years)
Surface: 10 m^2
Covering: 30%
Moss surface: 3 m^2
Moss type: Unknown (Tortula Muralis used)
Dry weight 3,556 kg
Water uptake: 21,820 liter
CO_2 uptake: 1,487 kg/year
CO_2 equivalent: From Delft to Scheveningen by bus

0,34 % evaporation will give a lowering of 5 °C air temperature 3m around the walkway

Case 10

What: A small bench
Where: Botanische tuin, Delft
Age: Unknown (+10 years)
Material: Bricks and mortar
Surface: 1,5 m^2
Covering: 25 %
Moss surface: 0,375 m^2,
Moss type: Hypnum
Dry weight: 0,199 kg
Water uptake: 2,477 liter
CO_2 uptake: 0,083 kg/year
CO_2 equivalent: From The Hague to Scheveningen by tram

0,45 % evaporation will give a lowering of 5 °C air temperature 3m around the walkway

Case 11

What:	A wall
Where:	Horst en Voordelaan, Voorschoten
Age:	Unknown (+10 years)
Material:	Concrete with cover
Surface:	7 m^2
Covering:	45 %
Moss surface:	3,15 m^2,
Moss type:	Tortula Muralis
Dry weight:	3,734 kg
Water uptake:	22,911 liter
CO2 uptake:	1,561 kg/year
CO2 equivalent:	From Delft to Gouda by local train

0,23 % evaporation will give a lowering of 5 °C air temperature 3m around the walkway

Chapter 10

Future potential

From experiments and calculations conducted in this case study it has been found that the moss specie *Hypnum Cupressiforme* takes up 0,222 kg of CO_2 per year per m^2 of moss concrete. Moss specie *Tortula Muralis* takes up 0,496 kg of CO_2 per year per m^2 of moss concrete. In this chapter these values will be used to determine the future possibilities of moss concrete. This chapter finishes with an impression of how this future can potentially look like.

10.1 Potential CO_2 fixation

The greening of the Netherlands

The annual CO_2 emission of an average citizen of the Netherlands is 15.900 kg [141]. If moss concrete should fixate all of this CO_2 emission, 4,5 soccer fields per person would be needed. Since 17,12 million people live in the Netherlands, this would mean that an area of 76,87 million soccer fields is needed in total to fixate the annual CO_2 emission of the Netherlands [144]. Unfortunately, the Netherlands has a total area of 5,82 million soccer fields, which is only 7,57 % of the total area needed to fixate the annual CO_2 emission, illustrated in table 10.1.

	Area (m^2)	**Number of soccer fields**
Moss concrete needed to fixate annual CO_2 emission per citizen in the Netherlands	32.056 m^2	4,49
Area available for each person in the Netherlands	2.418 m^2	0,34
Area needed to fixate the total emissions	550.722 km^2	76,87 million
Total area of the Netherlands	41.873 km^2	5,82 million
Area available in the Netherlands as percentage of total area needed to fixate annual CO_2 emission	(7,57%)	(7,57%)

Table 10.1: The area needed to fixate the annual CO_2 emission of the Netherlands

The greening of Dutch cities

The land area of the Amsterdam region is 165,50 km². A part of this land area can't be covered with moss concrete, such as roads, cycling lanes or pedestrian pavements. However, moss concrete can be applied on vertical surfaces, such as on building facades, on noise cancelling walls and on the side of constructions. If we assume that all horizontal surfaces where moss concrete can not be applied are replaced with vertical moss concrete surfaces, we can use the total land area of each city as an indication of potential CO_2 fixation. For Amsterdam the CO_2 uptake would be $36,74 * 10^6$ kg per year if all of Amsterdam is covered with *Hypnum Cupressiforme* moss, or $81,92 * 10^6$ kg if it is covered by *Tortula Muralis*. The annual CO_2 uptake if Utrecht, The Hague, Delft and Eindhoven would be covered with moss concrete and the CO_2 emission equivalent from this uptake is given in table 10.2. The World Health Organization recommends an amount of 50 m^2 of green area per person. This means that each person will fixate $11,1$ kg of CO_2 yearly when the *Hypnum Cupressiforme* specie is used, and $24,8$ kg when the specie *Tortula Muralis* is being used. In table 10.2 the potential CO_2 fixation of several cities in the Netherlands is given, as well as the equivalent in CO_2 emission.

City	Area	Moss specie	Annual CO_2 fixation (kg)	CO_2 emission equivalent
Amsterdam	165,5 km^2	Hypnum	$36,74 * 10^6$	5.400 rounds around the world by diesel car
		Tortula	$81,92 * 10^6$	Average emission of 5.200 citizens of the Netherlands per year
Utrecht	93,83 km^2	Hypnum	$20,83 * 10^6$	6.550 return flights from Amsterdam to Buenos Aires
		Tortula	$46,54 * 10^6$	Average emission of 2.300 US citizens per year
The Hague	82,45 km^2	Hypnum	$18,30 * 10^6$	10.700 times from Amsterdam to Tel Aviv and back by petrol car
		Tortula	$40,90 * 10^6$	Average emission of 1.160 citizens of the UAE per year
Delft	22,65 km^2	Hypnum	$5,03 * 10^6$	Emission of almost 600 homeless people in US per year
		Tortula	$11,23 * 10^6$	2.450 return flights from Amsterdam to Melbourne
Eindhoven	87,66 km^2	Hypnum	$19,46 * 10^6$	Average emission of 16.000 citizens of Indonesia
		Tortula	$43,48 * 10^6$	Average CO_2 in air 150.000 people breathe out

Table 10.2: Potential CO_2 fixation per city

From table 10.2 it seems that the yearly fixation for each moss covered city is quite high. However, if we compare this to the yearly emission from the inhabitants living in these cities, the actual impact can be seen. This is shown in table 10.3, and is often between 0,5-1,2 % yearly. An impression of a moss covered city is given in figure 10.5 on page 98.

City	Inhabitants	Yearly emission from inhabitants (kg)	Max CO_2 fixation yearly (kg)	Uptake (%)
Amsterdam	862.965	$13,63 * 10^9$	$81,92 * 10^6$	0,60 %
Utrecht	352.866	$5,572 * 10^9$	$46,54 * 10^6$	0,84%
The Hague	537.833	$8,492 * 10^9$	$40,90 * 10^6$	0,48%
Delft	101.030	$1,595 * 10^9$	$11,23 * 10^6$	0,704%
Eindhoven	231.642	$3,658 * 10^9$	$43,48 * 10^6$	1,19 %

Table 10.3: Impact of the CO_2 fixation per city

The greening of a dutch building

An estimate of the area of the front facade of the faculty of Civil Engineering and Geosciences at Delft University of Technology that can be covered with moss concrete is 1674 m^2. The annual CO_2 fixation of the front facade of CITG is compared to the annual CO_2 emission of the commuting of the employees, which can be seen in table 10.4. It is assumed that 60 % of all employees working at CITG live at 10 km distance and drive to work by petrol car. An impression of what the front facade of the faculty of Civil Engineering and Geosciences at Delft University of Technology would look like when covered in moss concrete is giving in figure 10.11 on page 101.

Annual CO_2 fixation of CITG and CO_2 emission from the commuting of the employees	
Estimate of the front facade covered with moss concrete	1674 m^2
Maximum CO_2 fixation of the mosses annually	830,3 kg
Employees working full time at the CITG faculty	616 FTE [145]
Estimate is that 60 % lives at 10 km from work	369,6 FTE
CO_2 emission of driving 10 km by petrol car	1,9 kg [140]
Daily emission of an employee living 10 km from CITG	3,8 kg
Daily emission of all employees living 10 km from CITG	1404,5 kg
Yearly emission of all employees living 10 km from CITG	365.176 kg
Annual CO_2 fixation of the moss covered facade as percentage of annual CO_2 emission from the commuting of the employees	**0,227** %

Table 10.4: Annual CO_2 fixation of CITG and CO_2 emission from transport of the employees

Conclusion on the future greening potential of the Netherlands

The annual CO_2 fixation as percentage of the total annual CO_2 emission on country, city and building level is between the 0,2-1,2%. There are several conclusions that can be drawn from this. The author draws the following conclusions from the found values:

1. People in the Netherlands emit an enormous amount of CO_2 annually. By lowering the CO_2 emissions, moss concrete will get a more prominent role in lowering the annual CO_2 emission. The CO_2 emitted when commuting is substantial, lowering this value will have an enormous impact on the lowering of the total CO_2 emission.

2. Although the annual CO_2 fixation as percentage of the total annual CO_2 emission does not seem much, it definitely contributes to the lowering of CO_2 emission of the Netherlands.

3. It is important to realize that moss concrete has several other positive effects besides CO_2 fixation. The air filtering capacity, increase in biodiversity, cancelling of the surrounding noise, water retention capacity, and improvement in mental and physical health are all positive effects of applying moss concrete. Therefore, the overall impact of moss concrete is very positive.

10.2 Future applications

Some barriers have to be overcome, if huge parts of the Netherlands are being covered with moss concrete without compromising on the structural capacity of roofs and facades. In section 4.4 *Drawbacks* on page 42 some of the drawbacks of moss concrete were already mentioned. For now the main concern is to provide a structure with enough durability to maintain its function throughout its intended service life. Until further research has been conducted to find out what the structural problems are if moss concrete is being used, some possible applications can already be thought off. Below some of the applications can be found that would allow moss concrete being used nowadays.

An extra cover layer

It has been found in the experiments of this research that insufficiently curing a low-clinker content concrete could lead to a stimulation of moss growth on the surface. The effect of curing goes as deep as 40 mm below the surface and has major effects on the microstructure of the concrete. Therefore it can be decided to add an extra cover layer, to prevent the durability of the structural bulk of the concrete to be in jeopardy. However, this leads to an increased amount of concrete being used. Since the production process of concrete is damaging, and emits CO_2, the effect of this extra cover layer is shown in table 10.5 for a layer of 40 mm, and in table 10.6 for a layer of 20 mm. This shows that although more concrete is being used, this will be fixated by the mosses in a couple of years, depending on the type of cment being used and the thickness of this extra cover.

40 mm extra cover	CEM I	CEM III/B
Per m^3 concrete	117,3 kg CO_2 emitted [146]	80,13 CO_2 emitted [146]
Per 0,04 m^3 concrete	4,692 kg CO_2 emitted	3,205 kg CO_2 emitted
Per m^2 moss concrete	max 0,469 kg CO_2 fixated per year	max 0,469 kg CO_2 fixated per year
Necessary years	10 years	6,8 years
After 50 years	18,758 kg CO_2 fixated per m^2	20,245 kg CO_2 fixated per m^2

Table 10.5: Emission and fixation of CO_2 for 40 mm extra cover

20 mm extra cover	CEM I	CEM III/B
Per m^3 concrete	117,3 kg CO_2 emitted [146]	80,13 CO_2 emitted [146]
Per 0,02 m^3 concrete	2,346 kg CO_2 emitted	1,603 kg CO_2 emitted
Per m^2 moss concrete	max 0,469 kg CO_2 fixated per year	max 0,469 kg CO_2 fixated per year
Necessary years	5 years	3,4 years
After 50 years	21,104 kg CO_2 fixated per m^2	21,847 kg CO_2 fixated per m^2

Table 10.6: Emission and fixation of CO_2 for 20 mm extra cover

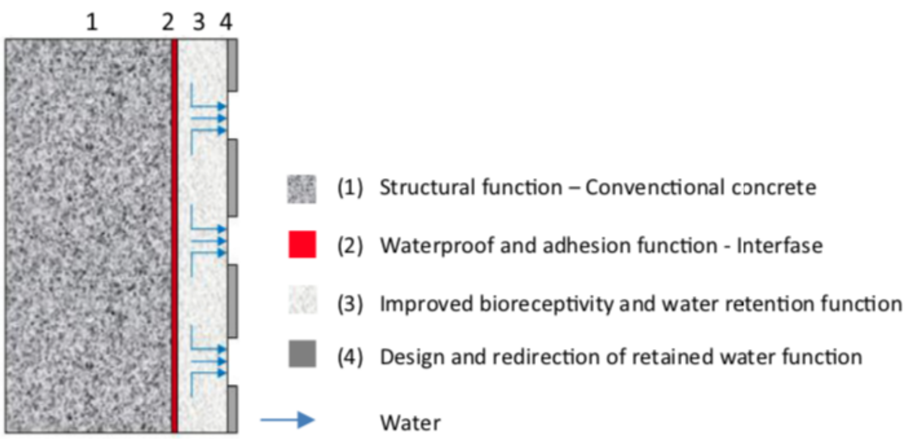


Figure 10.1: System to combine structural and bioreceptive concrete [21]

A combined wall system

Another option to stimulate moss growth without compromising on the durability is the use of a combined wall system. Manso et al. (2016) have been working on a system in which structural concrete is combined with the use of bioreceptive concrete, which can be seen in figure 10.1 [21]. Bioreceptive concrete is concrete that is especially designed to enable mosses to grow on it. This can be used as the outer barrier of the construction, while not function as structural concrete.

Figure 10.2: Prefabricated moss panels [22]

Moss panels

Panels of bio-receptive concrete can be fabricated, that can be placed on certain locations. These panels can be prefabricated in a laboratory with excellent moss growth conditions, thereby ensuring that there is moss present from the moment of placement. These panels enable the use of moss concrete not only on concrete constructions, but on all types of constructions, which is visualised in figure 10.2. However, it is important to realize that a moss concrete panel has a relatively high weight, therefore the structural capacity of the construction where it is placed must be verified beforehand.

Shot-green

On new and existing concrete structures an extra layer of non-structural bio-receptive concrete can applied, which can be called *Shot-green*. Just like the combined wall system, a bio-receptive concrete mixture should be made that will enable abundant moss growth on the structure. This will result in a green facade with all the perks of moss concrete, without compromising on the structural capacity. The bioreceptive concrete can be distributed on the structure just like shotcrete, which can be seen in figure 10.3, or as a paste or a coating. This will enable existing buildings to turn green. Only a thin layer of the *Shot-green* has to be applied, from which the effects can be seen in table 10.7 which are conventional since the amount of cement used is probably lower in the *Shot-green* mix design.

Figure 10.3: Applying shot-green [23]

5 mm Shot-green	CEM I based	CEM III/B based
Per m^3 concrete	117,3 kg CO_2 emitted [146]	80,13 CO_2 emitted [146]
Per 0,005 m^3 concrete	0,587 kg CO_2 emitted	0,401 kg CO_2 emitted
Per m^2 moss concrete	max 0,469 kg CO_2 fixated per year	max 0,469 kg CO_2 fixated per year
Necessary years	1,2 years	0,8 year
After 50 years	22,86 kg CO_2 fixated per m^2	23,05 kg CO_2 fixated per m^2

Table 10.7: Emission and fixation of CO_2 for a 5 mm *Shot-green* cover

10.3 Future scenarios

The future of cities

Large parts of a city can be covered with moss concrete. This will result in a lowering of the UHI effect, contribute to the formation of ecosystems, lower the surrounding noise and mitigate the air pollution. The increased aesthetic value will enable a lowering in stress levels, thereby lowering the physical effects of high stress.

Figure 10.4: Current situation [24]

Figure 10.5: The future of cities [24] *(Altered by author)*

The future of infrastructure

The impact of infrastructure on the road users and local residents would change completely if all concrete surfaces are covered with moss, illustrated in figure 10.7. This abundant moss growth will enable a reduction in noise from the vehicles, filter particles from the air, fixate CO_2, and contribute to a pleasant surrounding for the road users and surrounding neighbours. This could lead to a lowering of stress levels and irritations on the road, thereby decreasing the chance of accidents and stress related symptoms.

Figure 10.6: A present day highway junction [25]

Figure 10.7: The future of infrastructure [25] *(Altered by author)*

The future of the industry

The application of moss growth on concrete in industrial areas can lead to an improved view for surrounding neighbours, which can contribute to a decrease in mental health problems. Thereby, the mosses can mitigate the air pollution and lower the surrounding noise.

Figure 10.8: Current view for surrounding neighbours [26]

Figure 10.9: The potential future view for surrounding neighbours [26] *(Altered by author)*

The future of buildings

Mosses can be used on the facades of buildings. This will not only contribute to the cooling and insulation properties of a building, but also improve its aesthetics and contribute to a lowering in the surrounding noise. In the section 10.1 *Potential CO_2 fixation* on page 93 the potential uptake of the faculty of CITG is calculated. An impression of what the front facade would look like covered in moss concrete is given in figure 10.11.

Figure 10.10: Current situation [27]

Figure 10.11: The future of buildings [27] *(Altered by author)*

The future of architecture

The future of architecture can be changed by moss concrete. Extra architectural value can be created with mosses growing in patterns on concrete, visualised in figure 10.13. This can be obtained with the use of different sorts of moss species, or combining concrete parts where moss growth is stimulated with parts where it is inhibited.

Figure 10.12: The current situation [28]

Figure 10.13: The future of architecture - using patterns [28] *(Altered by author)*

The future of marketing

If patterns can be created with concrete, texts or logos could be grown as well. This will not only change the future of Architecture, but also change the future of marketing. Imagine that green facades can be used as billboards throughout the city. An example of what a text and logo in moss concrete could look like is given in figure 10.14.

Figure 10.14: The future of marketing - using text and logos [28] *(Altered by author)*

Part IV

The final part

Chapter 11

Conclusion

Humanity has drawn benefits of nature for millennia, without causing any global disruptions. However, due to the industrialization and growing consumption this has changed in the past centuries. The presence of humans on earth can be felt virtually everywhere, on biological, chemical and physical levels. Moreover, this leads to the disruption and loss of ecosystems, which has a severe effect on the surrounding environment. Proper city design could help to mitigate climate change, lower energy consumption, protect the biodiversity and provide a safe and healthy environment for its inhabitants. The greening of outside walls and roofs of buildings and structures will contribute to a sustainable and livable city.

In this research moss growth on concrete has been investigated as potential means for facilitating green walls and roofs. At the start of this research two research questions have been formed to serve as guidelines throughout this thesis. To answer both research questions a mixed approached has been applied, that combines knowledge obtained from the literature study of chapter 2 *Sustainable cities*, chapter 3 *Concrete*, and chapter 4 *Moss concrete*, with conducted experiments and a case study. In this chapter both research questions have been answered.

11.1 Answering research question 1

The first research question to be answered:

1. What are the most influencing material properties of concrete that determine the presence or absence of abundant spontaneous moss growth on current relative young concrete constructions, and how can these factors be influenced to either stimulate or inhibit moss growth?

Several factors have been found that influence the moss growing process on the concrete surface, visualised in figure 11.1. The aim of this research is to find how this hospitable concrete surface unconsciously is created in practice.

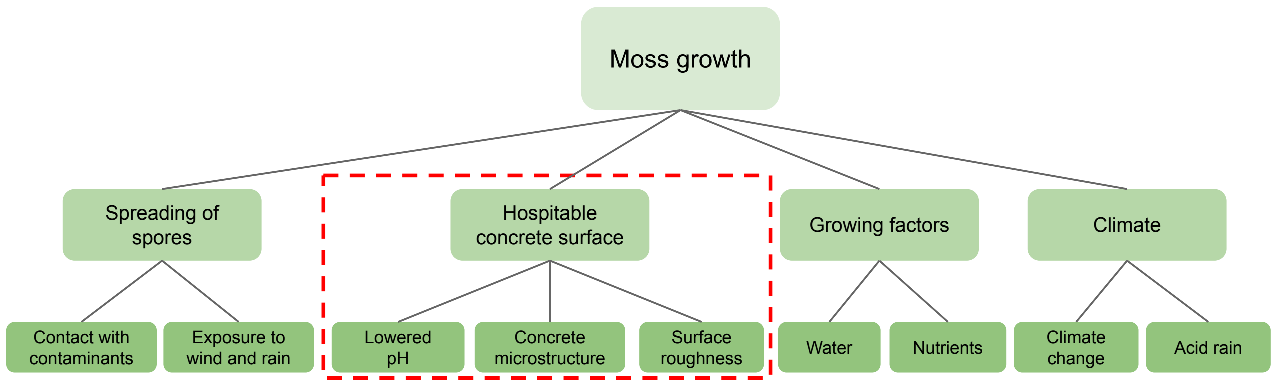


Figure 11.1: Influencing factors on the formation of a biofilm *(Author's figure)*

It has been found in this research that the curing conditions and the cement type being used are two factors that greatly influence the micro-structure of the cover zone of concrete. An appropriate micro-structure can contribute to the presence or absence of abundant moss growth on current relative young concrete constructions. In literature the positive relation between moss growth and concrete with a porous and permeable cover zone was found [29]. The origin of this accidentally obtained porous and permeable concrete surface was unknown. A porous and permeable cover zone will enable a high level of water absorption and retention. This creates an optimum environment for micro-organisms and vegetation to settle on, because moisture is provided for a long period after it has been raining [82].

In this thesis experiments have been conducted to analyse what could have caused this porous and permeable cover zone of concrete. From the results it can be concluded that a low-clinker content concrete that is insufficiently cured (meaning in this research air cured or paraffin cured), will give a porous and permeable cover zone from a relatively early age on. Low-clinker content concretes are relatively very vulnerable for insufficient curing, causing 98,56 % more water absorption than when the samples are water cured. High-clinker content concretes are relatively less sensitive for insufficient curing, an increase in absorption of only 29,09 % is found when high-clinker content samples are air cured instead of water cured. This is caused, among others, by the slow hydration process of low-clinker content concretes and the carbonation process. The rate of carbonation is higher for insufficiently cured concrete. In addition, the carbonation of low-clinker content concrete will lead to a more porous and permeable cover zone, while concrete with a high-clinker content is compacted by carbonation.

A second effect that the use of low-clinker content concretes give to stimulate moss growth is the relatively low buffering capacity towards alkalinity. Concrete with a low buffering capacity towards alkalinity is unable to neutralize incoming acid, thereby enabling the pH at the cover zone of the concrete to drop. This leads to a more attractive concrete cover for micro organisms to settle on.

Stimulating moss growth on concrete

To obtain concrete that is bioreceptive and enables mosses to grow on its surface, a low-clinker content concrete must be used that is insufficiently cured (air curing or paraffin curing). Although there are several (environmental) factors that determine the presence or absence of moss growth on concrete, visualised in figure 11.1, the chances of moss growth on concrete will be significantly higher when a low-clinker content concrete that is insufficiently cured is used. This will cause a porous and permeable outer layer of the concrete, that has been related to moss growth on concrete. Due to the low buffering capacity towards alkalinity, the pH at the cover zone of the concrete will be lower, thereby making the surface more attractive for micro organisms to settle. An additional effect of insufficient curing is the increase in carbonation, which leads to a more porous and permeable cover zone for low-clinker concrete. In figure 11.2 the effect that the low-clinker concrete mix together with insufficient curing has is visualised.

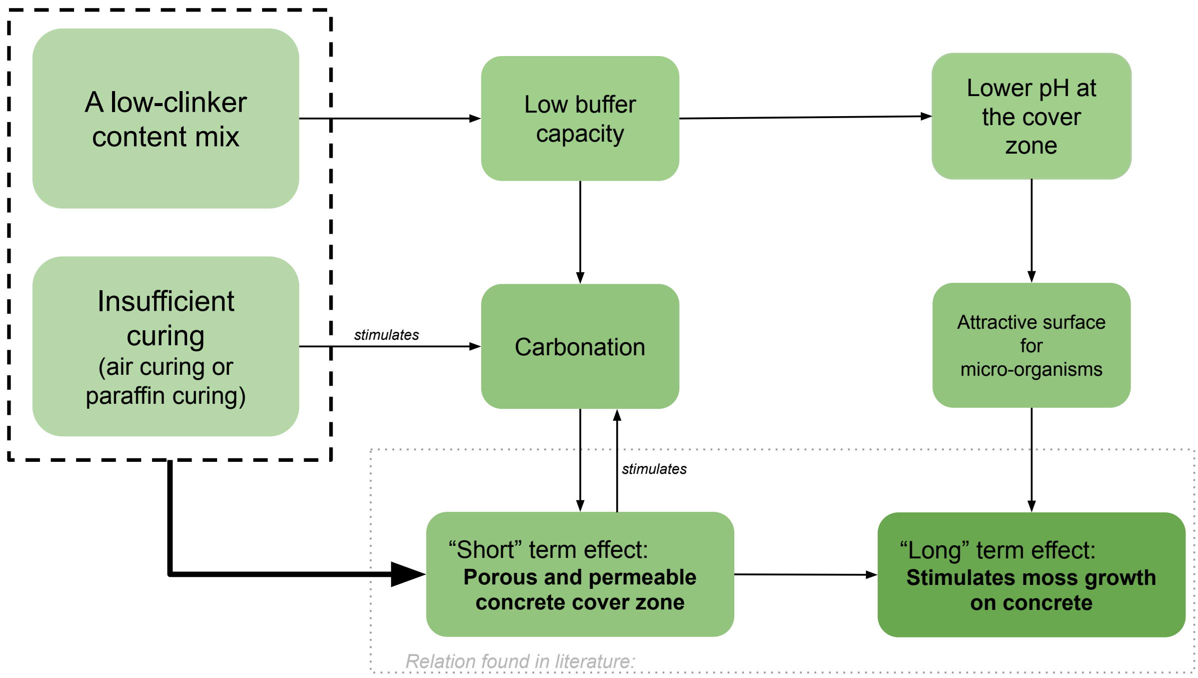


Figure 11.2: Stimulating moss growth on concrete *(Author's figure)*

Inhibiting moss growth on concrete

To inhibit moss growth on concrete, a dense microstructure and a high pH at the outer layer of the concrete must be created. This can be obtained by using a high-clinker content concrete, which is visualised in figure 11.2. From this research it can be concluded that a high-clinker mix is relatively not very vulnerable for the curing conditions. A high-clinker content concrete will provide a dense microstructure and high buffer capacity towards alkalinity, even though it has been cured insufficiently. When a low-clinker concrete is being used in practice and moss growth is unwanted, the sample concrete should receive excellent curing conditions, this can result in a very dense microstructure, that might be able to keep acid and other harmful substances out.

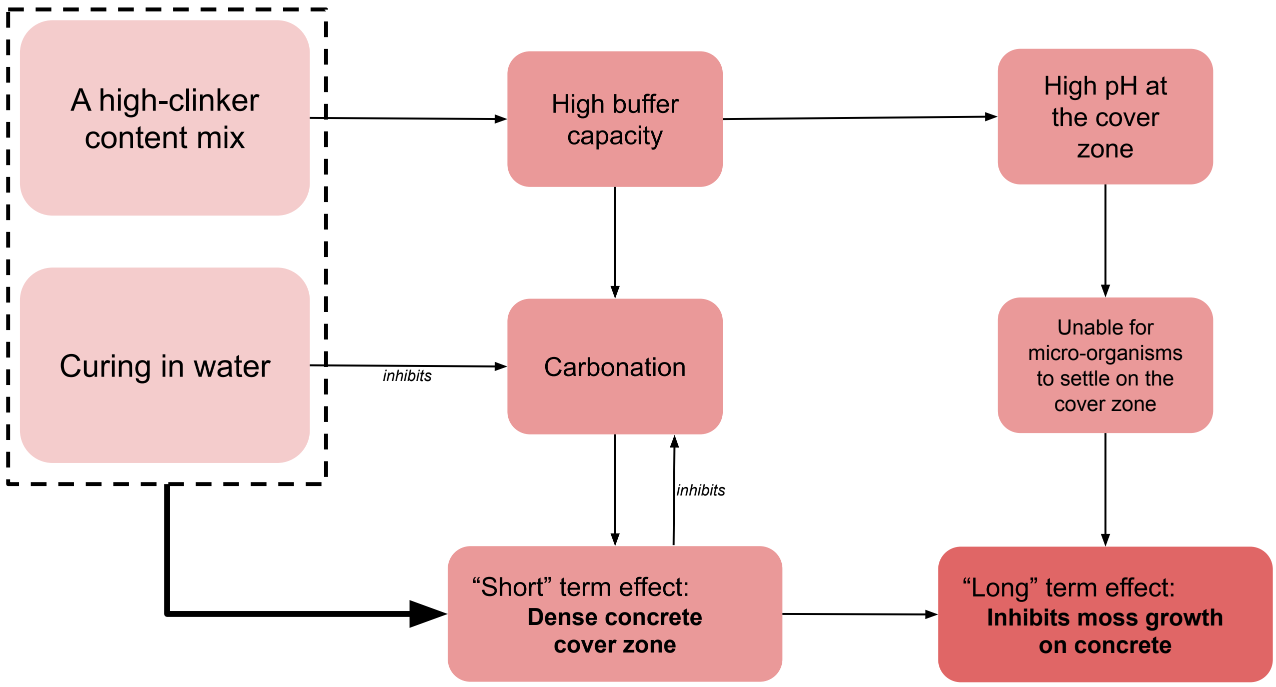


Figure 11.3: Prevention of moss concrete *(Author's figure)*

11.2 Answering research question 2

The second research question to be answered in this research is:

2. What are the most important environmental performances of concrete with abundant moss growth, and can these environmental performances be quantified to gain more insight in the necessity of moss concrete in cities?

The environmental performance of concrete with abundant moss growth on it has been investigated in this research. The air filtering capacity of mosses will lead to an improvement of the respiratory system, by absorbing fine particles of 10 μm and smaller that would otherwise be accumulated in the alveoli of the lungs. A lowering of 23% of asthma and COPD patients have been found amongst citizens that are surrounded by green. Mosses fixate CO_2 in order to produce biomass. The acoustic properties of mosses contribute to a lowering of the community noise. An estimate of the noise reduction when green roofs are being used is typically 3 dB, which is equivalent to half of the cars on the road, or half of the driving speed. The water retention capacity of mosses contribute to the cooling of buildings during summer, and provide insulating properties. An elevated amount of green space will lead to an improvement in mental and physical health. A decrease in anxiety disorder has been found of 31 % when exposed to 90 % of green space instead of 10 %. Thereby, the biodiversity will be increased if more green is applied in urban areas. Due to the water absorption capacity of mosses, urban flooding can be mitigated or even prevented.

In the case study executed in this research, the water absorption capacity and CO_2 fixation of moss covered constructions have been quantified for eleven structures. In addition, the potential CO_2 fixation on country, city and building level is calculated. The potential of the annual CO_2 fixation as percentage of the total annual CO_2 emission on these levels is between 0,2-1,2%.

The author draws the following conclusions from the literature, the conducted experiments and the case study:

1. Moss concrete has several very important qualities that will contribute to more sustainable cities and mitigate climate change. The air filtering capacity, increase in biodiversity, cancelling of the surrounding noise, water retention capacity, and improvement in mental and physical health are all positive effects that occur when moss concrete is applied.
2. Moss concrete contributes to a lowering of the Urban Heat Island effect, due to the transpiration of the leaves and an increasing in the albedo. Using moss concrete will improve the living environment of city inhabitants and multiple animal species.
3. People in the Netherlands emit an enormous quantity of CO_2 annually. By lowering the CO_2 emissions, moss concrete will get a more prominent role in lowering the annual CO_2 emission in the Netherlands. The CO_2 emitted during commuting is substantial. Attention could be payed to lower by employers, thereby contributing to more sustainable companies.

The overall conclusion of this research is that the implementation of moss concrete will lead to positive effects on physical, mental and environmental levels. Moss concrete enables humanity to contribute to restoring the negative consequences of our parasitic behaviour, and allows us to thrive in a more mutualistic relationship with planet earth.

Chapter 12

Recommendations

Executed experiments

Looking back on the executed experiments in this research, some recommendations can be made:

- In this research, three types of mortar mixes have been used, that differed in clinker content. However, two of the mixes were quite similar. The clinker content in the CEM III/B mix was 27-32 % and in the CEM III/B + fly ash mix the clinker content was 25,9-30,7 %, compared to a 95-100 % clinker content in the CEM I mix. This research would be more significant if one of the low-clinker content mixes would have had a higher amount of clinker, for example a clinker content of 60 %. This would lead to three situations, a high-, middle- and low- clinker content, instead of only the high- and low-clinker content that is used now in this research. It would be interesting to find out if the middle-clinker content mix would behave as the average of the other two mixes, or that it would resemble the high- or low-clinker content mix.
- A recommendation that can be made is to cast mortar cubes with sides of 150 *mm* each, instead of the prisms of 40x40x160 *mm* that have been used now in the experiments. These 150 *mm* cubes allow cores to be drilled from the surface, for example with a diameter of 70 *mm*. The use of these cores in the experiments will diminish the effect of curing on the sides of the samples, and will lead to more clearly defined surface and core parts, visualised in figure 12.1.

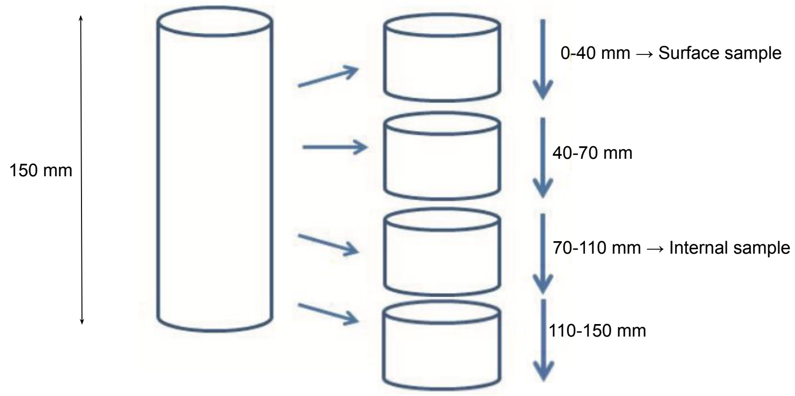


Figure 12.1: The use of cubes of 150 *mm* allow cores to be drilled from the surface. This leads to more clearly defined surface and internal samples [29] *Altered by author*

- In the original plan of this research it was planned to perform each executed test in threefold, to get an significant outcome. One extra specimen was made per variable, in case something went wrong. However, during this research extra tests have been added for different reasons, such as the carbonation test and the epoxy impregnation, for which specimens were needed of each variable. A recommendation that can be made is to make more extra specimens, since the carbonation test and epoxy impregnation test now have been executed only once. If these tests would have been repeated a couple of times, the results would be more significant.

- In this research the effect of the curing conditions have been tested on several durability parameters, since previous research has shown that the durability parameters are more sensitive for insufficient curing than strength testing [118] [119]. During strength testing the bulk of the material will be tested, while durability parameters enable a focus solely on the cover zone. If strength testing was performed as part of the experimental program of this thesis, a comparison could have been made on the effect that insufficient curing has on the strength compared to the durability parameters. This could possibly show that based on strength testing the concrete could be declared sufficient, while the durability parameters clearly show the detrimental effect of insufficient curing. This will be further discussed in the part below.
- The curing compound has now been spread on the cover of the concrete after the surface water has disappeared, since this is what the manufacturer recommends. However, from the results it has been shown that in some cases specimens treated with a curing compound are actually more porous and permeable than specimens that have been air cured. Applying the curing compound directly after casting might have resulted in more optimal curing conditions for the specimens, since it has been found in literature that the time of application will influence the effectiveness of the curing compound [133]. On the other hand, this might lead to other reactions and complications taking place. Therefore, applying the curing compound at two different moments would show the differences.
- The used curing compound is now a paraffin based curing compound. Using a different kind of curing compound might have led to different results. Xue et al. (2015) found that composite-based and acrylic-based curing compounds perform better than paraffin-based curing compounds [132].
- In this research a lot of time was spend on preparing specimens for the Mercury Intrusion Porosimetry test, and executing this test. Unfortunately, the MIP machine broke down after a couple of measurements. When the machine was finally fixed, the glassware needed for the samples of this research was not available, and had to be order. In addition, it turns out that the MIP test is very sensitive for applying too much or too little of the sample, thereby ruining a four hour measurement. All these factors together led to the waste of a lot of time on MIP measurements. The author advises researchers to not use MIP tests if these are not strictly necessary.

Recommendations for further research

Some recommendations for future research originated from this research:

- Currently, the concrete quality is monitored on strength. A certain strength must be reached by the young concrete when the codes are being followed, which will ensure a certain service life. However, a possible new research topic could be if the concrete quality shouldn't be monitored on durability properties as well as on strength. This can lead to new insights, in which the question must be raised if only strength testing is sufficient enough to estimate the quality of concrete.
- In this research the porosity, permeability and the buffering capacity of high- and low-clinker content specimens have been investigated when insufficiently cured and water cured in an early stage. However, the insufficient curing of (low-clinker) concrete could lead to additional effects on the concrete specimens, early on as well as on the long-term. Other mechanical and durability parameters could be tested, contributing in closing the knowledge gap that exists between the literature and laboratory testing, and what actually happens in practice.
- From the results of this experiments it can be seen that the curing compound has a detrimental effect on the porosity and permeability of a concrete. A reaction between the paraffin-based curing compound and the mortar specimen might have occurred. However, the possibilities of such a reaction must be investigated since it can't be explained from the experiments executed in this research. Further research with different curing compounds should be executed to elucidate the phenomenon observed when specimens are cured with a curing compound in this research.
- De Belie et al (1996) concluded in their research that Ordinary Portland Cement (CEM I) is more vulnerable for an acid attack than CEM III/B based cement [134]. However, in their research the concrete samples were exposed to four cycles of a strong acid attack (pH = 2/3) and after each phase the surface was brushed to detach unstable concrete [134]. The amount of material that was lost during brushing showed the resistance against acid attack, in which CEM III/B based samples came best out of the test, and CEM I samples as worst. However, it must be noted that all specimens first received excellent curing conditions (28 days of RH 90%/20 °C), leading to a very dense pore structure of low-clinker content samples compared to CEM I samples. To combine the effect of the microstructure with the buffering capacity towards alkalinity, this experiment should be repeated with specimens that are air cured and cured with a curing compound. This will show the actual effect of CEM III/B based samples when placed in an acid environment, since in practice concrete is often insufficiently cured.

- In this research the CO_2 capture and water absorption of mosses have been quantified. However, there are more environmental performances that can be quantified specifically for moss concrete, for example the increase in biodiversity, the air filtering capacity, and the reduction of surrounding noise. This will make the implementation of moss concrete higher on the agenda of the construction industry.

Appendix A

Results

A.1 Drying behavior

In figure A.1 the hourly rate of moisture loss for the surface samples can be found for the first 5 hours of the experiment. While the results for CEM I samples lie relatively close to each other, the results for CEM III/B and CEM III/B + fly ash samples show relatively a large scatter between the different curing conditions. While curing in water results in a lower speed of moisture loss for CEM III/B and CEM III/B + fly ash compared to CEM I, air curing result in a higher speed of moisture loss for CEM III/B and CEM III/B + fly ash compared to CEM I.

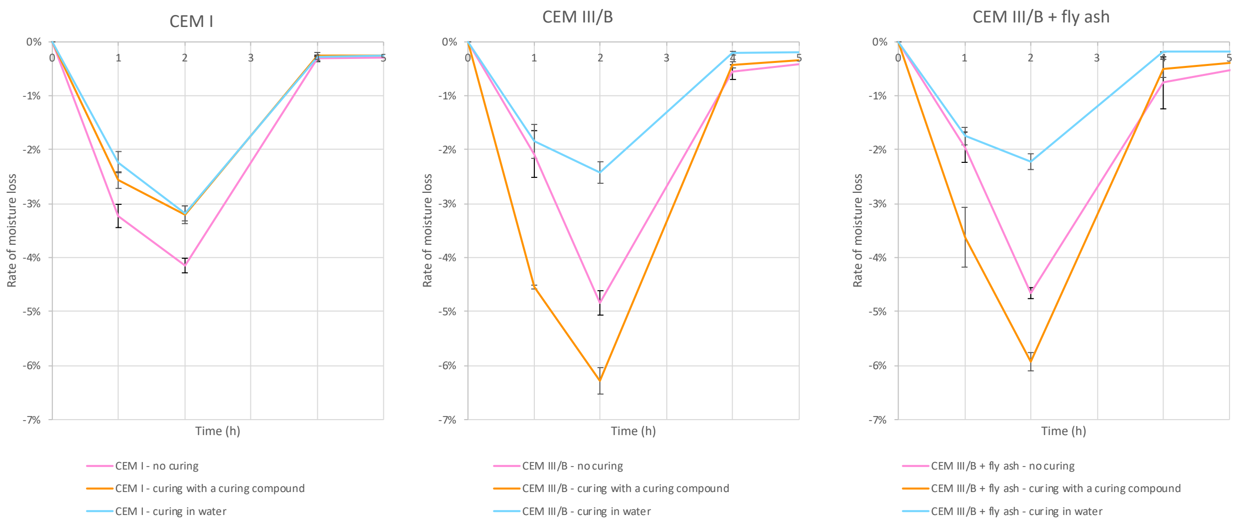


Figure A.1: Moisture loss speed of the surface samples - binder type

In figure A.2 the hourly speed of moisture loss is visualised for the core samples, categorized on binder type. Comparing the speed of moisture loss for surface samples, visualised in figure A.1, and core samples, visualised in figure A.2, the surface samples have an increase in speed during the first two hours, while the core samples only in the first hour. The results lie closer to each other for the core samples in comparison to the surface samples.

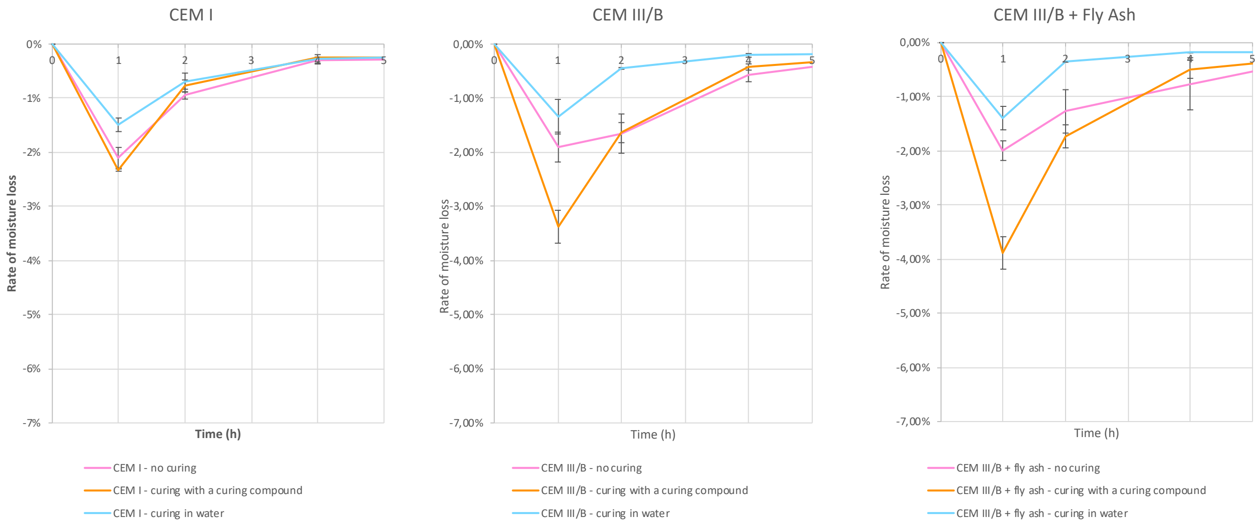


Figure A.2: Moisture loss speed of the core samples - binder type

A.2 Buffer capacity tests

In figure A.3 the amount of acid that is added per minute to the solution is illustrated, categorized on curing type. It can be observed that for each curing method, CEM I can take up most of the acid. The behavior of CEM III/B and CEM III/B + fly ash is very similar for all curing conditions.

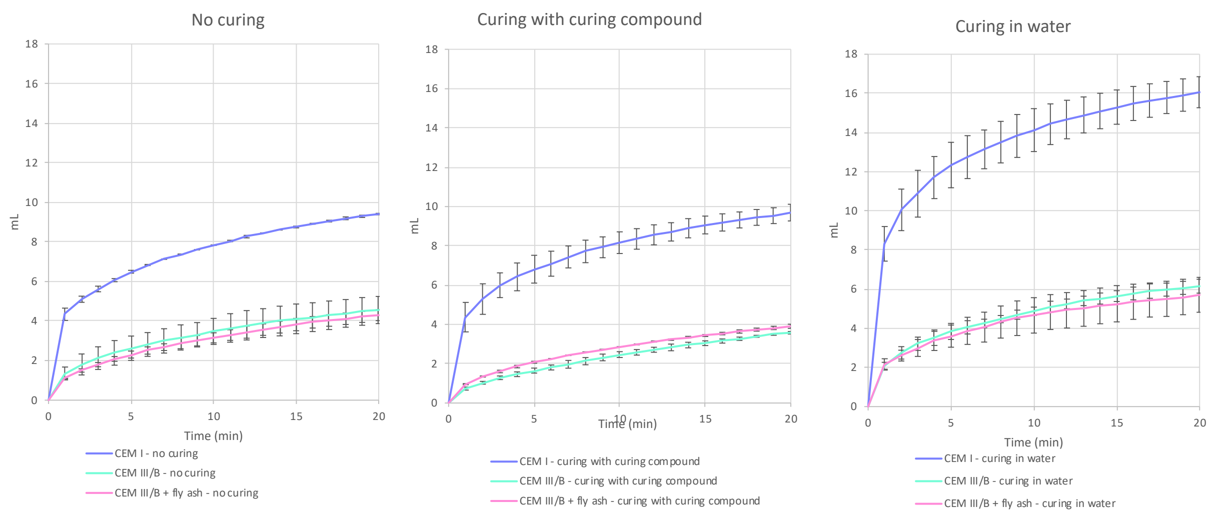


Figure A.3: Added mL to keep the pH at 7 - curing condition

A.3 Moss testing

In figure A.4 the reaction speed of the moisture loss of the mosses can be observed. It can be seen that during the first two hours the rate of reaction increases, after which the reaction gradually slows down. The shape of the graph is similar to the reaction speed of the mortar specimens.

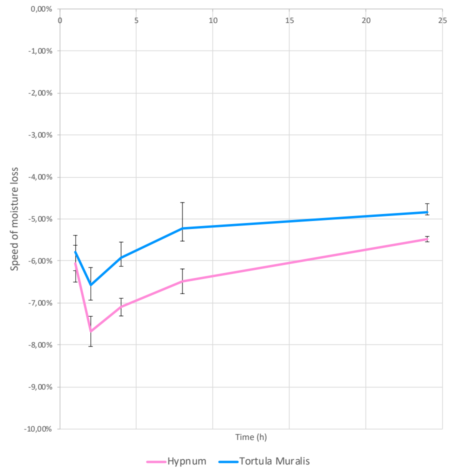


Figure A.4: Reaction speed mosses

In figureA.5 the moisture loss as % of dry weight is given for three mortar specimens that haven't cured, and for the two moss species. It can be seen clearly that the moisture loss of the mosses is relatively much higher than the moisture loss of the mortar specimens. It also shows that the moss specimens don't seem to slow down in reaction speed as long as there is still moisture available.

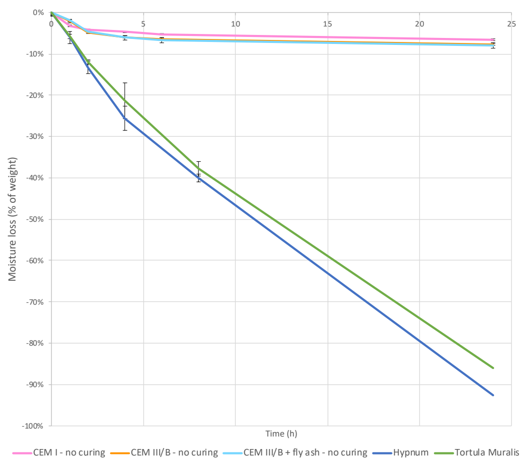


Figure A.5: Comparison of moisture loss

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