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# STRENGTH DEVELOPMENT OF CONCRETE: BALANCING PRODUCTION REQUIREMENTS AND ECOLOGICAL IMPACT

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**Abstract.** The effective production of concrete structures requires adequate control of strength development in order to realise the scheduled production cycles. Demoulding of elements can take place only when sufficient strength is gained and the production cycle has to be maintained with seasonal changes of temperature. The use of Portland Cement promotes high early age strengths, but comes with a relative high impact on the environment since decarbonation and a high energy demand come along with cement production. Supplementary cementitious materials have been widely applied to improve the sustainability of concrete but the rate of early age strength development often is compromised to some degree.

An experimental study was executed with the aim to maintain a similar strength level at early age but lowering the content of Portland clinker in concrete. Parameters of the study were the replacement level of Portland Cement, the curing temperature and the use of strength accelerator. At a comparable workability level, specimens were produced of which the compressive and flexural strengths were determined at different ages after casting. The Dutch CUR tool 'Green Concrete 3.2' was used to determine the environmental impact of the mixtures. The results show that concrete can have a much lower impact on the environment without compromising on the production conditions. Quantifying the trade-off between the use of Portland Cement and other mixture components and adding heat in the process is important information in order to balance production requirements and the ecological impact of concrete structures.

## 1 INTRODUCTION

The advantages of concrete are freedom of shape, possibilities to integrate other functions and components, to build structures with limited maintenance costs, ease of use and very high durability. A significant reduction of the environmental impact can convince owners to choose concrete rather than other building materials. Ecological aspects like the protection of resources, material recycling and a long technical life-time of structures are important for our society; owners and contractors are aware of not only the benefits related to the environment by producing environment-friendly structures but many include environmental targets in their business strategy. With the production of Ordinary Portland Cement (OPC) comes high $CO_2$-emissions. A very effective way to reduce the environmental impact of concrete is to replace OPC by alternative binders. For example, the hydraulic activity of ground granulated blast furnace slag (GGBS) was already known in 1862 [1]. In the Netherlands, GGBS-cement is a common cement type, which has been successfully applied in many large-scale infrastructure projects. In other countries, such as Norway, fly ash (FA) is a more common additive in concrete. Considerable volumes of OPC have already been replaced in concrete by supplementary materials, but the effect is compensated by the still rising demand for concrete worldwide. In order to improve the sustainability of products and structures made with concrete, alternative solutions have to be developed. Such solutions are also required from the economic point of view in order not to lose market share to other materials. General agreement has to be achieved concerning the assessment method and quantification of the environmental impact; an example of impact indicator is the Environmental Product Declaration (EPD). The development of such 'instruments' requires a coordinated and cooperative approach of different countries.

Production efficiency is a distinct characteristic and requirement of the precast industry and many in-situ cast concrete structures. Due to its chemical composition and hydraulic reaction, the use of OPC ensures relatively high early age strengths. In order to compensate for a lower strength at early age caused by clinker replacement, an appropriate curing regime and/or a hardening accelerator have been applied. This study was executed in order to determine the potential for a reduction in environmental footprint by cement replacement without compromising on the (early age) strength development. The energy-efficiency of concrete was quantified with the parameter 'relative strength cost' that relates the environmental impact and the compressive strength of concrete. The discussion on the environmental impact of concrete based on only the mixture composition might seem isolated not taking into account the total life cycle of a structure but it indicates the potential for an optimization on the material level.

## 2 ENVIRONMENTAL IMPACT QUANTIFICATION

Large differences can be identified worldwide with regard to the methods applied and progress in quantification of the environmental impact of the construction sector and the recognition thereof. In the future, it probably will be common practice to include such approaches in tenders and contracts. A life cycle analysis has to consider many aspects. In order to compare buildings or concrete structures it is necessary to weight different aspects with regard to environmental impact and to express them in the same unit: costs in Euro being an obvious choice. According to the Dutch law 'Bouwbesluit' the depletion of raw materials and emission of greenhouse gases has to be determined for new buildings and renovation projects. A national database has been established in the Netherlands [2], which can be applied to quantify the environmental impact of infrastructures. In addition, the CUR-tool 'Green Concrete' [3] was developed by SGS Intron for CUR Commission B-88 and it is the base to produce EPD's. The tool aims at users who want to determine the environmental impact of structures, structural elements and products made with concrete. It is also a tool to optimize concrete and concrete structures with regard to the environmental impact. The user chooses building materials and processes from a database; with own data, the database can be extended. For the calculation of the environmental cost parameter MKI (Dutch: Milieu Kosten Indikator) eleven environmental impact categories from LCA data in a building product EPD are taken into account with conversion factors that reflect their relative effect. Table 1 lists the eleven parameter and accompanying conversion factors. The outcome of MKI-calculations are costs in Euro/unit. The MKI is a factor already taken into account in the Netherlands for the tender of community works as well as for office buildings.

**Table 1**: Eleven environmental impact categories and MKI conversion factors

| **Nr.** | **Impact category** | **Abbreviation** | **Unit** | **Conversion factor** [Euro/kg] |
|---|---|---|---|---|
| 1 | Abiotic Depletion, fuels | ADP | kg Sb eq | 0.16 |
| 2 | Abiotic Depletion, minerals | ADP | kg Sb eq | 0.16 |
| 3 | Acidifying Pollutants | AP | kg SO2 eq | 4 |
| 4 | Eutrophication Potential | EP | kg PO4 eq | 9 |
| 5 | Freshwater Aquatic Eco-Toxicity Potential | FAETP | kg 1,4-Dichlorobenzene eq | 0.03 |
| 6 | Global Warming Potential, 100 years | GWP 100 Y | kg CO2 eq | 0.05 |
| 7 | Human Toxicity | HTP | kg 1,4-Dichlorobenzene eq | 0.09 |
| 8 | Marine Aquatic Eco-Toxicity Potential | MAETP | kg 1,4-Dichlorobenzene eq | 0.0001 |
| 9 | Ozone Depletion Potential | ODP | kg CFC11 eq | 30 |
| 10 | Photochemical Ozone Creation Potential | POCP | kg Ethylene eq | 2 |
| 11 | Terrestrial Eco-Toxicity Potential | TETP | kg 1,4-Dichlorobenzene eq | 0.06 |

The Global Warming Potential (GWP) is the environmental impact category often referred to as the carbon footprint. Table 2 shows the weight of $CO_2$ produced per unit of concrete component according to [3].

**Table 2**: Conversion factors GWP and assumed transport distances for concrete components

| **Component** | **Abbreviation** | **Type** | **Reference in database** | **Distance** | **GWP** [kg $CO_2$ eq] | **Per unit** |
|---|---|---|---|---|---|---|
| CEM I 52.5 R | CEM I | Binder | SBK CEM I-NL | 186 (T) | 8.2E-1 | kg |
| CEM III 52.5 | CEM III | Binder | CEM III-A NL | 186 (T) | 4.4E-1 | kg |
| GGBS, Orcem | GGBS | Binder | SBK Hoogovenslakken | 150 (T) | 1.9E-2 | kg |
| Fly ash | FA | Binder | Poederkoolvliegas c2 | 150 (T) | 3.3E-3 | kg |
| Limestone, powder | LS | Binder | Kalksteenmeel (BE) | 150 (T) | 2.2E-2 | kg |
| Limestone, gravel | | Aggregate | Kalksteen (BE) | 230 (S) | 2.3E-3 | kg |
| River sand | | Aggregate | Zand (D) | 200 (S) | 3.8E-3 | kg |
| Water | | Water | Leidingwater | 0 | 3.4E-4 | kg |
| Accelerator | ACC | Admixture | Plastificeerder | 150 (T) | 3.9E-1 | kg |
| Superplasticizer | SUP | Admixture | Superplastificeerder | 150 (T) | 7.2E-1 | kg |
| Ship (S) | | Transport | Binnenvaartschip | | 4.6E-2 | km |
| Truck (T) | | Transport | Truck, empty retour | | 1.3E-1 | km |

The applied very fine OPC CEM I 52.5 R 7000 requires more grinding to reach the higher fineness compared to the reference Portland cement CEM I 52.5 R. No detailed information was available with regard to the production and an overall 15% increase in $CO_2$-emissions was accounted for this binder type for additional grinding.

## 3 EXPERIMENTAL SET-UP

The experimental study, described hereafter, was a part of a larger program [4] and consisted of producing and testing fifteen mortars, which had a comparable flowability and which were tested at different ages in the hardened state (flexural and compressive strengths). The study was based on a 100% Portland Cement (CEM I 52.5 R) reference mixture. The applied OPC has a high early strength and it is often applied in prefabrication for example to produce prefabricated prestressed elements. Table 3 shows the composition of the binder in mortar; OPC cement was replaced by weight. The water-cement ratio of the reference mixture (100% OPC) was 0.45; the same water dosage was applied for all mixtures (the water-binder ratio always was 0.45). The volume percentage of the sand in mortar amounts 48.5 Vol.-%. In order to enhance the early age strength development, four hardening accelerators were selected and tested: BASF Master X-seed 100 (B), Sika Rapid C-100 (S), Mapefast CF/L (M) and Demula ACCEL IF (D); the dosage was determined based on the product sheets and was fixed at 80% of the optimal prescribed dosage, equal to 0.32, 2.40, 1.58 and 2.40 kg for each 100 kg binder material, respectively.

**Table 3**: Binder composition in mortar [Weight-% of binder]

| Nr. | CEM I | CEM I+ | CEM III | Slag | LS | FA | ACC |
|---|---|---|---|---|---|---|---|
| **1** | 100 | | | | | | |
| **2** | 90 | | | | 10 | | |
| **3** | 70 | | | 30 | | | |
| **4** | 70 | | | 30 | | | B |
| **5** | 70 | | | 30 | | | S |
| **6** | 70 | | | 30 | | | M |
| **7** | 70 | | | 30 | | | D |
| **8** | | 85 | | | 15 | | |
| **9** | 28.6 | | 71.4 | | | | S |
| **10** | 70 | | | | | 30 | |
| **11** | 70 | | | | | 30 | S |
| **12** | | 15 | 85 | | | | S |
| **13** | 15 | | 85 | | | | B |
| **14** | 20 | | 75 | | 5 | | B |
| **15** | 15 | | 85 | | | | S |

The mineral composition of the binders (with the exception of the limestone powder) is given in Table 4. The dosage of superplasticizer (BASF: Glenium 51) of the mortars was adjusted in order to obtain a flow spread of 250±20 mm. Since several mixtures were also tested as concretes, a similar paste consistency assured that the test results are not significantly affected by differences in workability. Two types of Portland Cement were tested: CEM I 52.5 R HES (Holcim) and CEM I 52.5 R 7000 (Heidelberg); the latter cement was much finer. Besides, limestone powder OMYA Betocarb and fly ash class F were applied.

**Table 4:** Composition of binders and cement replacing materials [Weight-%]

| **Component [weight-%]** | **CEM I 52.5 R HES** | **CEM I 52.5 R 7000** | **CEM III/A 52.5 N** | **GGBS Orcem** | **Fly ash** |
|---|---|---|---|---|---|
| $CaO$ | 62.1 | 65.5 | 53.6 | 38.6 | 3.0 |
| $SiO_2$ | 17.3 | 22.6 | 26.3 | 29.3 | 54.2 |
| $Al_2O_3$ | 5.5 | 3.9 | 7.0 | 11.6 | 23.5 |
| $Fe_2O_3$ | 3.8 | 1.4 | 1.6 | 1.5 | 7.9 |
| $MgO$ | 0.8 | 0.8 | - | 8.0 | 1.9 |
| $Na_2O$ | 0.4 | 0.2 | - | 0.2 | 1.1 |
| $K_2O$ | 0.7 | 0.7 | - | 0.5 | 3.4 |
| $Na_2O$-equivalent | | | 0.8 | | 3.3 |
| $SO_3$ | 3.4 | 3.4 | 3.6 | 0.02 | 0.9 |
| $CL^-$ | 0.03 | <0.1 | 0.07 | 0.007 | 0.003 |
| $MN_2O_3$ | | | | 0.3 | |
| $S^{2-}$ | | | | 1.3 | |
| $P_2O_5$ | | | | | 0.3 |
| Loss on ignition | 1.2 | 1.4 | 0.5 | 1.5 | |
| Insoluble rest | 0.4 | 0.7 | 0.2 | 0.8 | |
| Blaine-value [$m^2/kg$] | 500 | 740 | 550 | 396-450 | |

The mortars were prepared with a 5 litres Hobart mixer according to the following procedure: Binder materials and water were added first in the bowl; the mixing starts at a low speed of 145 rounds per minute (rpm) for 60 s. Afterwards, sand is added steadily during the next 30 s and mixing continues for 30 s at a mixing speed of 145 rpm. Then, the mixer was stopped for 90 s, during the first 30 s, the mortar adhering to the wall is re-added to the cement paste by making use of a scraper. Then a rest period of 60 s was kept. During this rest period, the superplasticizer is added to the cement paste. At the end, the paste is again mixed at a speed of 145 rpm for a period of 90 s.

Directly after mixing the flow spread was determined according to NBN EN 12350-8 [5] (dimensions of cone: height: 60 mm; upper/lower diameters: 70/100 mm). The flow test was executed on a smooth wooden plate (formwork 'betonplex'), which was moistened just before filling the cone. When the target flow of 250±20 mm was not reached, an extra amount of superplasticizer was added to the cement paste. Then, the paste was remixed for 60 s after which a rest period of 60 s is applied before conducting the flow test again. This step was repeated until the flow spread was within the acceptance range; the maximum number of remixing steps was two. With the required flow spread, test specimens were cast. A mould consists of three prisms (height/width: 40 mm; length: 160 mm). The mortar was agitated for 60 s by making use of a jolting apparatus. The temperature effect was studied by curing at three different levels (20/35/50°C). The mortars that were cured at room temperature were stored in a room with an average relative humidity of 93±5% and a temperature of 20±2 °C. Heat treatment during the first 18 hours was executed by storing moulds in a container filled with water for a steam curing cycle. The moulds were placed on a sieve plate above the water level. The water was gradually heated at heating rates equal to 20 °C/h and 24 °C/h for temperatures of 35 °C and 50 °C, respectively. After 18 hours of heat treatment and until testing at 28 days, the prisms were cured in a climate room with a temperature of 20±2 °C and a relative humidity of 93±5%. Flexural and compressive strengths of the prisms were determined according to NBN EN 196-1 [6]; the applied testing machine was a 'Walter+bai ag' compression machine. After the execution of the flexural test (three-point bending) on prisms the specimen broke into two parts which were both subjected afterwards to a compression test. The compressive and flexural strengths of the mortars were determined after 18 hours of curing and for an age of 28 days.

## 4 RESULTS AND DISCUSSION

### 4.1 Mechanical testing

The compressive strengths of 15 mortars in function of the curing temperature are shown in Figures 1 and 2. The highest strength level at 28 days was obtained for all curing temperatures with a mixture of the fine Portland cement (CEM I+), the slag cement and S-accelerator (M12); with the same combination the highest compressive strength was obtained after 18 hours and for a curing temperature of 50°C. The lowest strength level at 28 days for all curing temperatures was found for mixtures produced with a 30% replacement by fly ash and with or without an accelerator (M10&M11); for M10 (20°C) no experimental values could be determined after 18 hours, since the strength was very low. With the exception of Mixtures M3 and M13, the differences in strength after 28 days for the same mixture but different curing temperatures were moderate; M3 and M13 showed relatively high differences in compressive strengths obtaining the highest strengths for curing temperatures of 20°C. At 28 days, the compressive strength was often slightly higher for the 20°C curing cycle, a result that can have consequences and has to be taken into account for the mix design when applying the same mixture in different curing regimes.

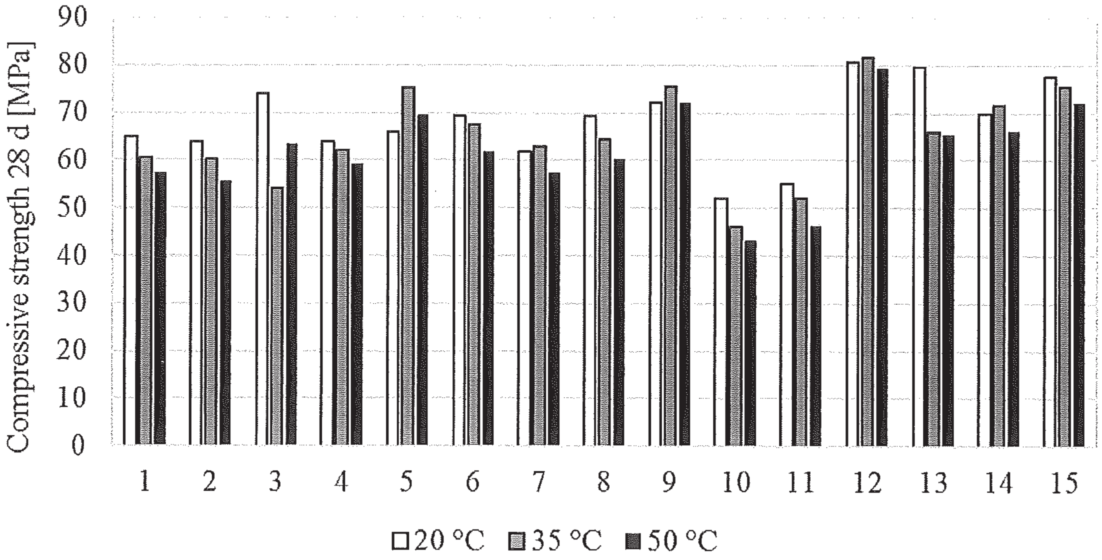

**Figure 1**: Comparison of compressive strengths (28 days after casting)

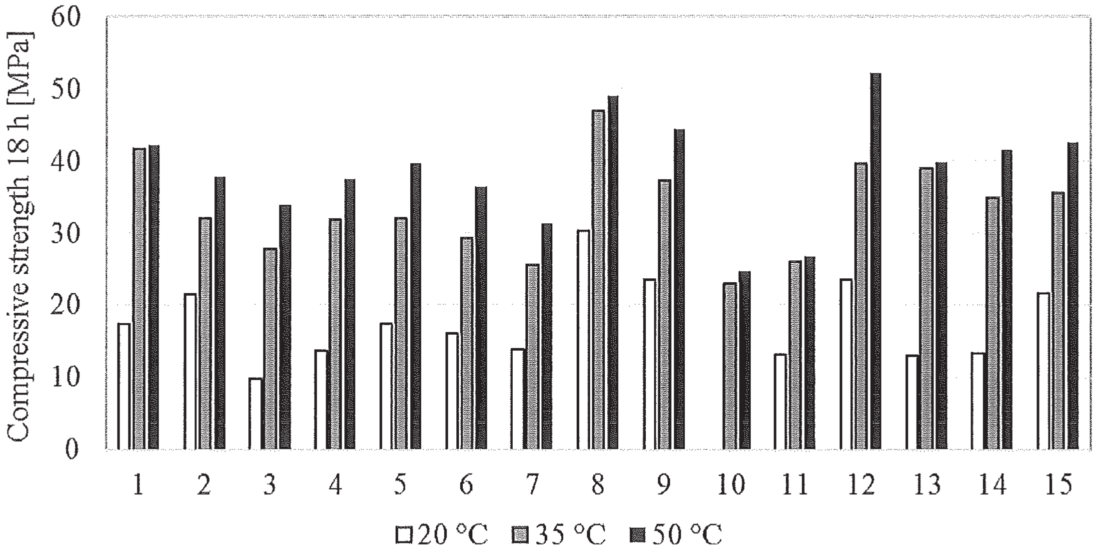

**Figure 2:** Comparison of compressive strengths (18 hours of curing)

Focussing on the early age strength (Figure 2), higher strengths (compared to M1) were obtained with Mixture M2 for 20°C (10% limestone powder replacement), replacement by finer cement (M8&M12) and the replacement of OPC with CEM III/GGBS and use of S-accelerator (M9&M15). Especially, the last combination (M15) realised a significant reduction in environmental footprint. Limestone powder has a beneficial influence on the $C_3S$-hydration during the first 15 hours [7,8]. The dilution effect caused by the lower cement content in limestone powder containing pastes is overruled by the filler action and the additional nucleation sites generated with the limestone powder addition. Technical and economic benefits were realised with M2, but it was only a moderate benefit with regard to the environmental impact. In case of a 15% limestone powder replacement, the dilution effect could have compensated the early age compressive strength benefit, which was the reason that the finer cement type CEM I 52.5R 7000 having a fineness of 740 $m^2/kg$ was applied for M8. The replacement of CEM I by GGBS (30% replacement level) reduced the early age strength independent of the curing temperature (M3); the addition of an accelerator (M4-M7) reduced the difference compared to the reference mixture. The largest reduction of the difference was obtained with the S-accelerator (M5) for all curing temperatures; at 20°C a comparable strength level with the reference mixture was obtained. Due to the higher activation energy of slag-blended mortars, the influence of heat curing on their strength development is more pronounced at 50°C compared to Portland Cement containing mortars. As a consequence, the difference in strength at higher temperatures is less pronounced. Mixtures M9 and M15 can be considered most optimal when taking into account environmental impact, economic aspects and level of compressive strength. Since Mixture M15 realises a higher cement replacement (35% slag content compared to 30% in case of Mixture M9) it is considered to be preferable. Heat curing also showed a pronounced effect on the strength of the reference mixture; the difference between 35°C and 50°C was small. The binder composition of concrete affects the strength development in the curing range of 20°C to 50°C hereby providing possibilities for the optimization of the curing regime. The largest strength difference for the three curing regimes was obtained for Mixture M12 combining the effects of accelerator, OPC fineness and higher activation energy.

Table 5 shows the test results with regard to flexural strengths after 18 hours of curing and 28 days after casting. For both compressive and flexural strengths similar trends were observed (the results that were higher than the flexural strength of M1 are bold and underlined). Mixture M12 performed very good with regard to compressive and flexural strengths at different ages und with changing curing conditions. The most optimal mixture (M15) with regard to performance, economy and environmental impact containing 35% of slag by a replacement with CEM III/A 52.5 N had early age compressive strengths at 18 hours of +24%, -15% and +1% for 20°C, 35°C and 50°C and flexural strengths at 18 hours of +29%, +8% and -9% for 20°C, 35°C and 50°C compared to the reference mixture M1, respectively. The flexural strengths of M15 at 28 days were lower for all curing temperatures compared to M1. The results in Table 5 show that the flexural strength at 28 days is less critical for mortars containing supplementary binders compared to 18 hours of curing - more mixtures reached at least the same strength level.

**Table 5**: Flexural strengths 18 hours and 28 hours after casting

| **T-curing** | **20 °C** | | **35 °C** | | **50 °C** | |
|---|---|---|---|---|---|---|
| **Mixture** | **18 h** [MPa] | **28d** [MPa] | **18 h** [MPa] | **28d** [MPa] | **18 h** [MPa] | **28d** [MPa] |
| **M1** | *3.40* | *6.82* | *5.38* | *6.40* | *5.04* | *6.27* |
| **M2** | **3.85** | 5.88 | 5.04 | 6.09 | 4.81 | **6.33** |
| **M3** | 2.04 | **8.15** | 4.52 | **7.16** | 4.93 | **7.29** |
| **M4** | 2.95 | **8.13** | **5.48** | **8.39** | **5.31** | **9.20** |
| **M5** | **3.84** | **8.63** | 5.27 | **8.78** | 4.50 | **8.36** |
| **M6** | 3.29 | **7.40** | 4.84 | **7.18** | 4.93 | **7.11** |
| **M7** | 2.61 | 5.85 | 4.50 | **6.72** | 4.16 | **6.79** |
| **M8** | **4.91** | **6.71** | 4.97 | **7.24** | 4.48 | **6.72** |
| **M9** | **4.57** | **8.14** | 4.99 | **8.83** | 4.40 | **8.81** |
| **M10** | 1.58 | 4.91 | 4.19 | 5.45 | 3.72 | 5.92 |
| **M11** | 2.62 | 4.25 | 4.39 | 5.01 | 4.20 | 5.31 |
| **M12** | **4.27** | **7.11** | **5.82** | **7.85** | **5.29** | **8.12** |
| **M13** | 2.77 | **7.02** | **6.31** | **7.09** | **5.43** | **7.60** |
| **M14** | 2.60 | **7.42** | **5.38** | 4.85 | **5.68** | 5.13 |
| **M15** | **4.38** | 4.58 | **5.81** | 5.19 | 4.57 | 4.98 |

## 4.2 Environmental impact

The environmental impact was assessed by making use of the CUR-tool 'Green Concrete 3.2'. The level of $CO_2$-emission as well as the environmental cost index MKI were determined. The total MKI score and $CO_2$-emmissions of the mixtures are composed of three individual contributions: production (use of components), transport of components and demolishment of elements; transport of prefabricated elements and the service phase are not taken into account for the calculations. The energy required for the curing of the mixtures was not considered in the calculations and the strengths were compared for the same curing regime. As Table 2 shows, the largest reduction in Global Warming Potential can be achieved with the replacement of Portland clinker since the emission value as well as the dosage in concrete are high. GGBS and FA have comparable and low emission levels. For the interpretation of the results it has to be considered that there is not (yet) a general consensus about the exact conversion values resulting in an uncertainty with regard to the calculation of MKI.

The Global Warming Potential of the reference mortar (M1) is 586 $kgCO_2/m^3$mortar; the MKI is 45.4 Euro/$m^3$mortar. Relative to the reference mortar, the most $CO_2$-reduction was realised with Mixtures M13&M14 (58% $CO_2$ of M1; 42% reduction) and M12&M15 (59% $CO_2$ of M1). Mixture M15 has a comparable cement replacement level, but the environmental cost index score is slightly higher due to the higher required dosage of the S-accelerator compared to the B-accelerator. The relative share of each component to the total MKI is shown in Table 6. The highest reduction in MKI (Table 6) was again achieved for Mixtures M13&M14 (66% of MKI of M1), whereas this were 69% relative to the MKI of M1 for M15. Differences in compositions are only reflected in a varying MKI in terms of production. For M15, the MKI related to the transport and the demolishment contribute 11% and 2% of the total MKI, respectively.

**Table 6**: Relative contribution to the environmental cost index score MKI of the production, transport of raw materials and demolishing phase

| Mixture | Production | Transport | Demolishment | Total | % to ref |
|---|---|---|---|---|---|
| **M1** | 41.26 | 3.42 | 0.68 | 45.36 | 100.00 |
| **M2** | 37.19 | 3.36 | 0.68 | 41.23 | 90.89 |
| **M3** | 29.78 | 3.28 | 0.67 | 33.73 | 74.37 |
| **M4** | 30.01 | 3.28 | 0.67 | 33.97 | 74.88 |
| **M5** | 31.22 | 3.28 | 0.68 | 35.18 | 77.55 |
| **M6** | 30.73 | 3.28 | 0.67 | 34.69 | 76.48 |
| **M7** | 31.22 | 3.28 | 0.68 | 35.18 | 77.55 |
| **M8** | 38.75 | 3.34 | 0.67 | 42.76 | 94.28 |
| **M9** | 29.68 | 3.39 | 0.67 | 33.75 | 74.40 |
| **M10** | 28.32 | 3.20 | 0.66 | 32.18 | 70.94 |
| **M11** | 29.71 | 3.20 | 0.66 | 33.57 | 74.00 |
| **M12** | 27.77 | 3.43 | 0.67 | 31.87 | 70.27 |
| **M13** | 25.96 | 3.39 | 0.67 | 30.02 | 66.19 |
| **M14** | 25.81 | 3.37 | 0.67 | 29.85 | 65.81 |
| **M15** | 27.25 | 3.43 | 0.67 | 31.35 | 69.11 |

As the strengths of the mixtures were not the same, in the following the ‘relative strength cost’ (the normalized environmental impact-to-strength ratio) is discussed. Since the early age strength level is especially important for prefabrication and the replacement of clinkers has a pronounced effect on this aspect, both environmental indicators are related hereafter to the 18 hours compressive strength. Figure 3 summarizes the results with regard to the ratio Global Warming Potential to early age compressive strength (Figure 4: ratio MKI to early age compressive strength). Significant differences are obtained; Mixtures M8, M9 and M12-M15 had the lowest Global Warming Potential and MKI. In several cases the ratio relative to the reference mixtures was below 50%. The relative difference between GWP and MKI was small, indicating the pronounced effect of GWP has on the environment.

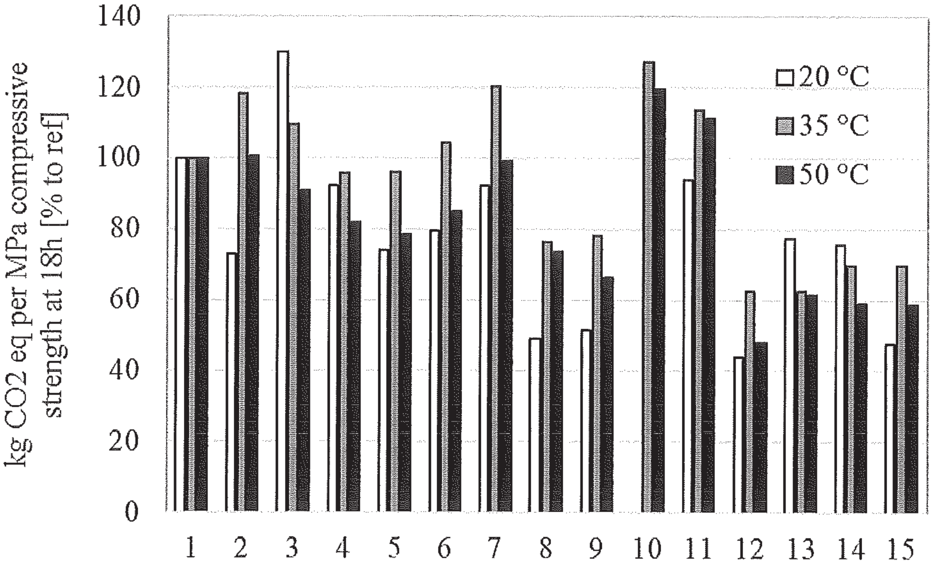

**Figure 3**: kg $CO_2$ emitted per MPa compressive strength after 18 hours of curing [% of reference mortar for each temperature]

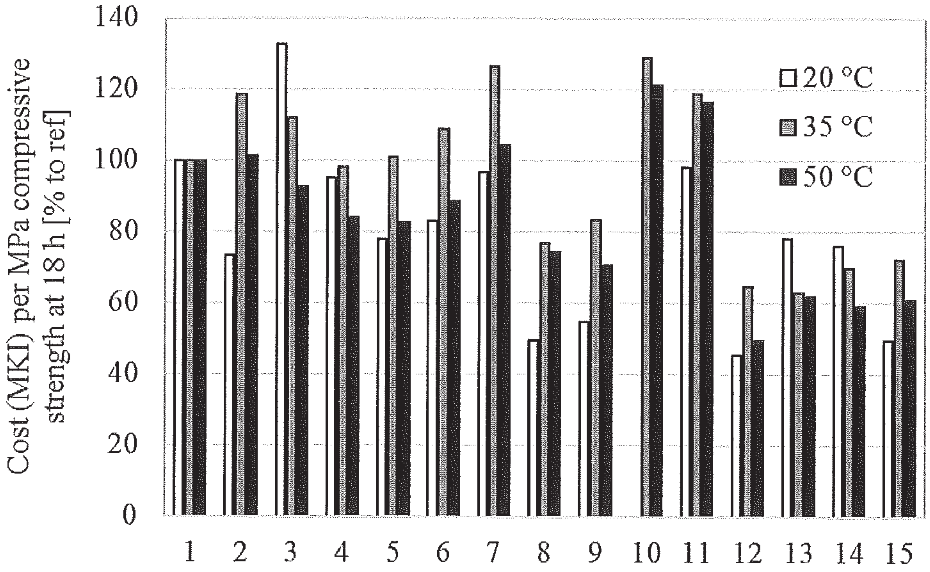

**Figure 4**: MKI per MPa compressive strength after 18 hours of curing [% of reference mortar for each temperature]

In practice, concrete contains coarse aggregates and less cement paste than mortar. For the present study the paste volume was assumed to be 30.5 Vol.-% compared to the 51.5 Vol.-% with which the mortars were prepared. Due to the higher cement paste volume of a cubic meter mortar, MKIs and $CO_2$-emissions of mortars are higher compared to the equivalent concretes. With the assumed paste volume of 30.5 Vol.-% one cubic meter of the reference concrete contains 397 kg CEM I 52.5 R, whereas one cubic meter of reference mortar contains 668 kg CEM I 52.5 R. The effect of the mixture composition on MKI and GWP caused by the production of one cubic meter of concrete and mortar for Mixture M1&M15 are depicted in Figure 5.

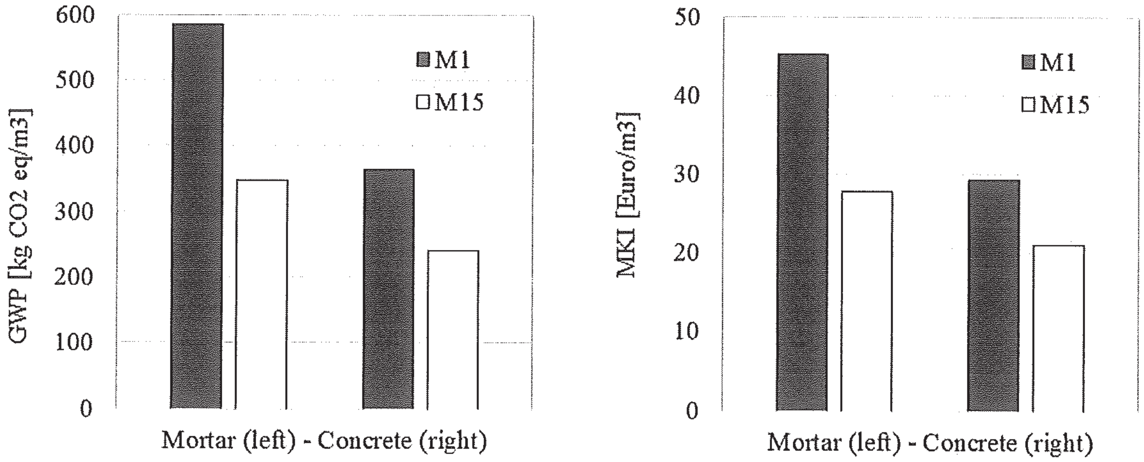

**Figure 5**: Global Warming Potential (a, left) and MKI score (b, right) per cubic meter of the reference concrete/mortar (M1) and the slag concrete/mortar (M15)

## 5 CONCLUSIONS

In an experimental study fifteen mortars with different binder compositions were tested with regard to their compressive and flexural strengths at different ages. The environmental impact was assessed and related to the compressive strength as a performance indicator. Based on the study the following conclusions can be drawn:

- The replacement of cement by fly ash decreased the compressive strength at 18 hours and 28 days. The compressive strength of a Portland cement-limestone powder combination was similar at both ages for a limestone replacement of 10%, the highest strength compared to the reference was obtained at 20°C.
- In order to realise a large reduction in environmental impact, ground granulated blast-furnace slag was tested as a cement replacing material. The addition of the hardening accelerator SIKA Rapid C-100 (containing of C-S-H nanoparticles) (partially) compensated the loss in early age strength. Due to the addition of a hardening accelerator, up to 35% of Portland cement can be replaced by blast-furnace slag at similar strength levels for different curing regimes.
- Mortars were produced at similar strength levels compared to a reference mixture containing only Portland Cement with a reduction of about 40% in Global Warming Potential and a 30% decrease of the environmental impact parameter MKI.

- The accumulation of different environmental impact parameters in a single number is a valuable method for the optimization of concrete.

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