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OPTIMIZATION OF CONCRETE FOR PREFABRICATION AND QUANTIFICATION OF ITS ENVIRONMENTAL IMPACT

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Abstract

The development of strength is an important criterion for the production of prefabricated concrete elements. With seasonal changes of temperature that affect the development of concrete strength, daily cycles of often 18 hours or shorter have to be maintained. The use of Ordinary Portland Cement (OPC) promotes high early age strength, but results in a relative high impact on the environment since cement production comes with decarbonation of components and a high energy demand. With the use of supplementary cementitious materials often comes a lower rate of strength development which might be compensated by one or more of the following measures: increase of cement fineness, curing at elevated temperature, optimization of the granular skeleton and/or use of accelerators.

An experimental study was executed to minimize the environmental impact of concrete while optimizing its early age strength development. Concrete containing 100% OPC was used as reference; tests were first executed on the mortar level and later transferred to the concrete level. The compressive strength was used as performance indicator; the heat of hydration of different mixtures was also determined on the mortar level. The environmental impact was quantified with two parameters: the emission of CO_2 per volume of concrete and an environmental cost indicator, which comprises eleven effects on the environment. The Dutch CUR tool 'Green Concrete 3.2' was used for the calculations of the environmental impact; the environmental cost indicator MKI is discussed in this paper. The results show that concrete elements can be produced with a much lower impact on the environment and without compromising on the production conditions. Taking into account the environmental impact is the basis for an optimization on the material level.

Introduction

Concrete is a relatively cheap and wide-spread building material with a variety of interesting characteristics like freedom of shape, possibilities to integrate other functions and components, to build structures with limited maintenance costs, ease of use and very high durability. In the hydraulic-binder system, OPC has a key function, but its use comes with 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. Both supplementary cementitious materials are too limited in volume to cover the worldwide increasing demand for cement. In order to improve the sustainability of products and structures made with concrete alternative solutions have to be developed. 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 relative high early age strengths. In order to compensate for a lower strength at an early age caused by clinker replacement, an appropriate curing regime [2] and/or a hardening accelerator [3] might be applied. This paper discusses the effect of mix design and curing conditions on the early age strength development and compares the relative reduction in environmental impact for different curing conditions.

General agreement has to be achieved concerning the assessment method and quantification of the environmental impact. The development of such methods requires a coordinated and cooperative approach of different countries. An example of impact indicator is the Environmental Product Declaration (EPD) and in the future it probably will be common practice to include instruments such as EPD's in tenders and contracts. In the Netherlands, a national database [4] has been established, which can be applied to quantify the environmental impact of infrastructures. With regard to the global warming potential, Wallevik et al. [5] defined different categories for carbon footprint, with 'EcoCrete-Xtreme' being the lowest category with not more than 105 kg CO_2-emissions per m^3 of concrete. In order to compare the environmental performance of concrete and to provide a base for the optimization of the mix design the environmental impact needs to be related to performance (i.e. the compressive strength). Aïtcin [6] defined the economic efficiency of concrete as cost for 1 MPa or 1 year of service life; Damineli et al. [7] applied the CO_2-intensity indicator and related the CO_2-emission and the compressive strength for the age of 28 days.

The two main objectives of this study were: 1) to determine the environmental impact of concrete with regard to the global warming potential and MKI-costs (calculated with the Dutch CUR-tool 'Green Concrete 3.2' [8]) and 2) to relate the environmental impact with the compressive strengths at 18 hours and 28 days. The replacement of OPC by alternative binder materials with a sufficiently high strength development enables the use of concretes with blended binders in the prefabricating industry. Quantifying the trade-off between the use of OPC and other mixture components provides important information to balance production requirements and to determine the environmental impact of concrete structures produced. A significant reduction of the environmental impact can convince owners to choose concrete rather than other building materials.

Environmental impact quantification

A Life Cycle Analysis considers all aspects with regard to the environmental impact during the different life stages of products and structures. EN 15804 [9] distinguishes seven environmental impact parameters, but does not provide any help how to weight them. The Dutch CUR-tool 'Green Concrete' [8] was developed to quantify the environmental impact, to weight different environmental aspects, which are then expressed in the same unit (the outcome is costs in Euro/unit volume) with the help of conversion factors. 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. The CUR-tool aims at users that want to determine the environmental impact of structures and structural elements made with concrete. It is also a tool to optimize concrete and concrete structures with regard to the environmental impact. It covers 1) production of components, 2) transport, 3) concrete production, 4) construction phase and 5) demolishing. The user chooses the building materials and processes from a database; with own data, the database can be extended. The MKI score and CO_2-emmissions of the mixtures discussed in this paper are composed of three individual contributions: production (only 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 heat curing of the mixtures was not considered in the calculations and the strengths are compared for the same curing regime. 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 shows eleven considered parameters and conversion factors. 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. CO_2-emissions (Global Warming Potential; GWP) have a significant influence on the environment and the MKI; GWP often is referred to as the 'carbon footprint'.

Table 1. MKI-conversion factors for 11 environmental impact categories [8]

Nr.	Impact category	Abbreviation	Unit	Factor [Euro/kg]
1	Abiotic Depletion, fuels	ADP1	kg Sb eq	0.16
2	Abiotic Depletion, minerals	ADP2	kg Sb eq	0.16
3	Acidifying Pollutants	AP	kg SO_2 eq	4
4	Eutrophication Potential	EP	kg PO_4 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 CO_2 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

Table 2 shows the reference database-sets of the Green Concrete tool [8] for global warming potential (GWP) and the applied concrete components. The numbers are industry-averages and might be lower or higher for the materials applied. The applied very fine OPC CEM I 52.5 R 7000 (CEM I+) requires more grinding to reach the higher fineness compared to the reference OPC CEM I 52.5 R (CEM I). 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.

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

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

Experimental set-up

The experimental part of the study consists of three parts: 1) variation of the mixture composition, determining of strength development and heat of hydration on mortar level, 2) transfer of selected mix designs to concrete level (measurement of strength) and 3) assessment and comparison of environmental impact of mortars and concretes. The compressive strength of fifteen mortars was determined at different ages (after 18 hours and 28 days). A mixture containing 100% OPC (CEM I 52.5 R) as binder was used as a reference mixture. The applied OPC has a high early strength and it is often applied in prefabrication for example to produce prefabricated prestressed elements. OPC was replaced by weight for the other binders; Table 3 shows the composition of binders in mortar.

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 water-cement ratio of the reference mixture was 0.45 (100% OPC); the same water dosage was applied for all mixtures (the water-binder ratio always was 0.45). The sand content of mortar was 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 applied was fixed to 80% of the maximum dosage according to the specific product sheets, equal to 0.32, 2.40, 1.58 and 2.40 kg for 100 kg of binder material, respectively. Two types of OPC were used: CEM I 52.5 R HES and CEM I 52.5 R 7000 (Table 4: CEM I+) having a fineness of 500 m²/kg and 740 m²/kg, respectively. The applied slag-blended cement type (CEM III) was a CEM III/A 52.5 N, which contains 57% of clinker, 42% of slag and 1% of filler; the Blaine surface area was 550 m²/kg. Slag (Orcem slag) was also applied for Mixtures M3-M7 (Blaine fineness: 400-450 m²/kg). Besides, limestone powder (OMYA Betocarb) and a Class F fly ash were tested. The mineral compositions of the binders (with the exception of the limestone powder) are shown in Table 4. Several mixtures were also tested as concretes and a similar mortar consistency assured that the test results are not significantly affected by differences in workability.

Table 4. Composition of binders and cement replacing materials (Weight-%)

Component [weight-%]	**CEM I CEM I**	**CEM I CEM I+**	**CEM III/A CEM III**	**GGBS Slag**	**FA 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 [m²/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 [10] (cone: H=60 mm; upper/lower diameters: 70/100 mm). The flow test was executed on a smooth wooden plate, 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 was applied before conducting the flow test again. This step was repeated until the flow spread was within the acceptance range; the maximum allowed number of remixing was two. With the required flow spread, test specimens were cast. A steel mould consists of three prisms (H/W: 40 mm; L: 160 mm). The mortar was agitated for 60 s by making use of a jolting apparatus.

Three different curing regimes were applied for mortar and concrete in this research: curing until testing in a climate room (20°C and 93 ± 5% humidity) and initially cured at 35°C or 50°C for 18 hours after which the mixtures were cured in the climate room. 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 [11]. After the execution of a three-point bending test on prisms the specimen broke into two parts which were both subjected afterwards to a compression test. The compressive strengths of the mortars are discussed in this paper and were determined after 18 hours of curing and at an age of 28 days.

Furthermore, concrete cubes (plastic moulds, size: 150 mm) were made based on the basic mortar compositions; three specimens were tested for each curing condition. The cement paste represents 30.5% of the total volume; the aggregate skeleton consisted of 35% sand 0/4, 44% limestone 2/6.3 and 21% of limestone 6.3/20 (numbers of fractions are mm). To ensure sufficient workability, superplasticizer was added if the slump was not at least 100 mm. The compressive strength of M1 and M15 were determined after 18 hours, 3 days and 28 days of hardening. The same curing cycle was applied for mortars and concretes.

Semi-adiabatic heat measurements were performed with a Langavant calorimeter, according to NBN EN 196-9 [12]. During this test, the specimen radiates heat to the environment which leads to the semi-adiabatic behaviour of the Langavant calorimeter. The apparatus is composed of two insulated flasks: the calorimeter and the reference calorimeter. They both are similarly constructed and have identical characteristics. The reference calorimeter contains a mortar box in which a sample of mortar is tested for at least 12 months before carrying out semi-adiabatic testing. The measurements of heat of hydration of the reference mixture (M1) is compared with the mortar showing the highest strength development (M8) and the mortar with the lowest environmental impact without compromising the compressive strength (M15).

Experimental results and discussion

Results on mortar level

Compressive strength of mortars

The average compressive strengths of the fifteen mortars after 28 days are shown in Figure 1. The highest strength level at 28 days was obtained for all curing temperatures with a mixture of the fine Portland cement (CEM I+), CEM III and S-accelerator (M12); with the same mixture the highest compressive strength was also 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% OPC-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 too low. With the exception of 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 and the highest strengths were obtained for curing temperatures of 20°C. At 28 days, the compressive strength was often slightly higher for the 20°C curing cycle, which has to be taken into account for the mix design when applying the same mixture in different curing regimes. Curing leads to a higher early age strength and a relatively lower strength at a later age, according to [13] this is caused by the rapid formation of hydration products in case of heat curing, resulting in a non-uniform microstructure with larger pore sizes.

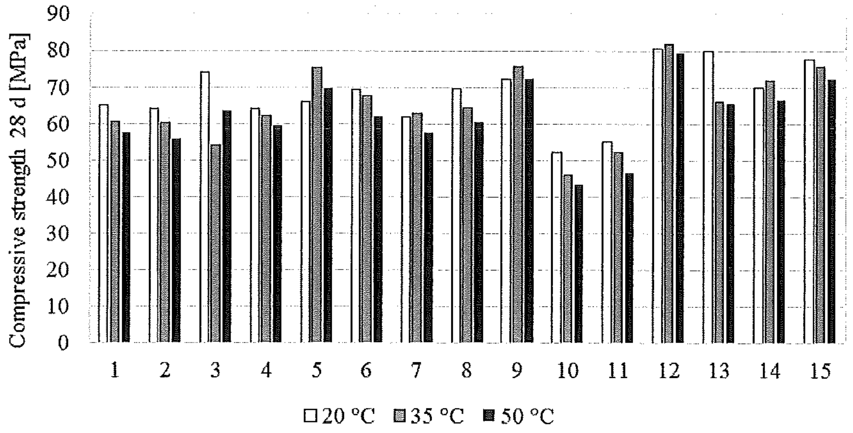

Figure 1. Comparison of mortar compressive strengths (28 days after casting)

Focussing on the early age strength (Figure 2), relatively higher strengths for 20°C curing (compared to M1) were obtained with Mixture M2 (10% limestone powder replacement), a replacement of OPC by finer cement (M8&M12) and the replacement of OPC with CEM III/GGBS and use of S-accelerator (M9&M15).

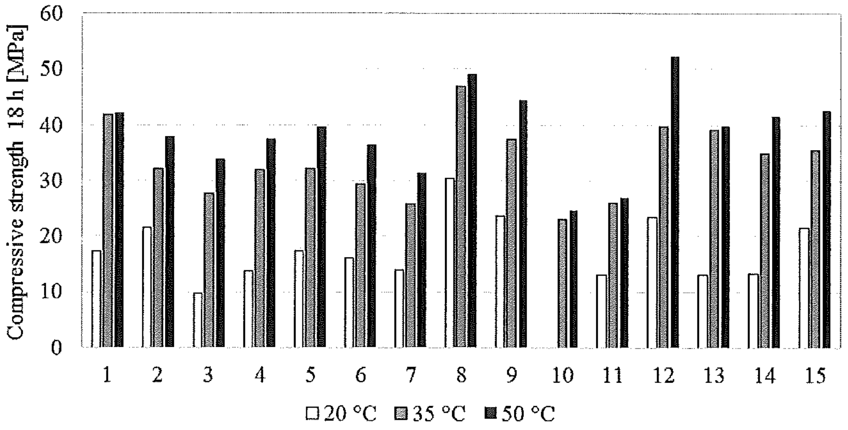

Figure 2. Comparison of mortar compressive strengths (18 hours of curing)

Limestone powder has a beneficial influence on the C_3S-hydration during the first 15 hours. 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 [14,15]. Technical and economic benefits were realized with M2, the benefit with regard to the environmental impact is moderate. In case of a 15% limestone powder replacement, the dilution effect could have overruled the early age compressive strength benefit, which was the reason that the finer cement type CEM I+ was chosen for M8. The replacement of CEM I by GGBS (30% replacement level) for M3 reduced the early age strength independent of the curing temperature; the addition of an accelerator (M4-M7) decreased the strength difference relative to the reference mixture M1. The largest decrease in difference for all curing temperatures for Mixtures M4-M7 was obtained with the S-accelerator (M5); for the 20°C curing a comparable strength level with the reference mixture was obtained. Heat curing also had a pronounced effect on the strength development of the reference mixture; the difference between 35°C and 50°C was small. Due to the higher activation energy of the slag-blended binder [13,16], the influence of heat curing on the strength development is more pronounced at 50°C compared to OPC. As a consequence, the difference in strength at higher temperatures is less pronounced with only OPC. 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.

Semi-adiabatic measurements

The heat of hydration was recorded with the semi-adiabatic calorimeter. The results of the examined mortars are represented in Figure 3 as a function of the equivalent time (calculated with the Arrhenius-equation for equivalent age).

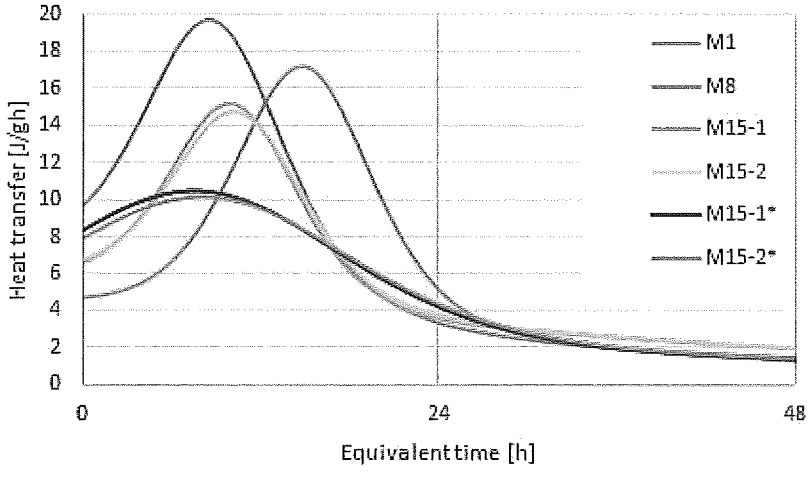

Figure 3. Curve fitting for heat transfer of mortars [J/gh]
(*: Assumed activation energy 47 kJ/mol instead of 33.5 kJ/mol)

The index (*) behind M15 indicates a higher assumed activation energy of 47 kJ/mol instead of 33.5 kJ/mol. The recording started 15 minutes after mixing and, as a consequence, the recorded heat transfer at the beginning of the measurements is not equal to zero. The first peak of hydration, which occurs at the moment of adding first water was not recorded. In order to obtain a gradual rate of heat transfer, Figure 3 is constructed after fitting of the cumulative heat to the binomial curve, which allows comparing the second peak of hydration for different mixtures. M8, containing the very fine CEM I+, further stimulated by the filler effect and the heterogeneous nucleation caused by the limestone addition, shows the highest activity resulting in an earlier and considerably higher peak value in hydration. The heat of hydration of M15 was measured twice in order to determine the repeatability of the test. The relative early peak of hydration can be mainly attributed to the presence of the chemical hardening accelerator; Darquenne et al. [17] also observed a relatively short induction period in case of slag-blended cement pastes. Increasing the activation energy from 33.5 kJ/mol to 47 kJ/mol results in a lower early age hydration rate due to the higher amount of energy required for the hydration reaction. Due to the hardening accelerator addition and the shorter induction period caused by the slag addition, the cumulative heat of hydration of M15 is higher compared to the reference mortar, after 15 and 20 hours for activation energies of respectively 47 kJ/mol and 33.5 kJ/mol.

Environmental impact of mortars

The environmental impact was assessed with the CUR-tool 'Green concrete 3.2' with regard to the carbon footprint and the parameter MKI. The largest reduction in CO_2-emission corresponds with the largest OPC replacement; the relative contributions of GGBS, fly ash and limestone powder are less than 3% compared to OPC. The Global Warming Potential of the reference mortar (M1) is 586 $kgCO_2/m^3$mortar; the MKI is 45.4 Euro/m^3mortar. Relative to the reference mortar, the most CO_2-reduction was realized with Mixtures M13&M14 (58% CO_2 of M1; 42% reduction) and M12&M15 (59% CO_2 of M1). M9 and M15 are preferred when taking into account the environmental impact, economic aspects and level of compressive strength; a higher cement replacement level was realized with M15 (35% slag content compared to 30%) compared to M9. Figure 4 shows the CO_2-emissions relative to the compressive strength after 18 hours, which are the 'relative strength costs' compared with the related value of reference mixture M1. The relative strength cost is not a specific number, but it is time-dependent, since the strength increases more or less in time. More mature concretes result in lower relative strength costs. In several cases and dependent on the heat curing, the ratio was below 50%.

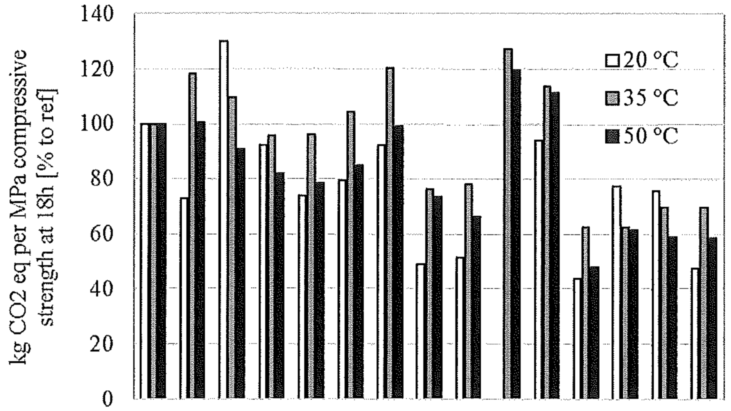

Figure 4. kg CO_2 emitted per MPa compressive strength after 18 hours of curing (% of reference mortar M1 for each temperature)

Table 5 shows the different contributions of mixtures M1, M8 and M15 to the MKI. The highest reduction in MKI was obtained for M15 with 69% relative to the MKI of

M1. The MKI contribution of the transport is in the range of 7-11% of the total MKI for all mixtures, whereas demolition is responsible for only 1-2% of the total MKI.

Table 5. Contribution to the environmental cost index MKI (Euro/m^3) 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
M8	38.75	3.34	0.67	42.76	94.28
M15	27.25	3.43	0.67	31.35	69.11

Results on concrete level

Compressive strength of concrete

Based on the results of the tests on the mortar level and the assessment of the environmental impact, Mixtures M1 and M15 were selected for further evaluation. The compressive strengths after 18 hours, 3 days and 28 days are shown in Table 6. Due to the higher activation energy of the slag blended concrete, curing resulted in a more pronounced increase in compressive strength at higher temperatures for M15 compared to the reference concrete M1. The lower initial strength of slag-blended concretes is caused by the slower puzzolanic slag reaction. Only when curing of 50°C was applied, the compressive strength of the slag-blended concrete after 18 h of curing was in the same range as the reference concrete M1. The addition of Sika Rapid C-100 hardening accelerator increased the compressive strength, but could not entirely compensate the dilution effect and the slower rate of hydration. In contrast, for mortar specimens and a curing temperature of 20°C, a higher compressive strength was obtained for M15 compared to M1. For 3 days of curing and with increasing curing temperature, the compressive strengths decreased for the reference concrete M1, which was not observed for the slag-blended concrete M15. After 28 days of hardening, the strength of M15 is at the same level of M1 for all curing regimes. When comparing the compressive strengths of concrete and mortar for M1 and M15 (cured with different temperatures and tested at different ages) the strengths were similar; slightly higher strengths were obtained for concrete specimens tested after 18 hours. However, the concrete strength of M1 after 18 hours for 20°C was much higher compared to the mortar specimens, which can be explained by the larger volume of concrete in the cube mould (plastic) compared to the mortar prisms (produced in a steel mould), which resulted in a higher heat of hydration during the first hours of hardening. As a conservative approach, preliminary concrete design can take place based on mortar compressive strengths.

Table 6. Comparison between compressive strength of slag-blended concrete (M15) and the reference concrete (M1)

Test	20°C		35°C		50°C	
after	M1	M15	M1	M15	M1	M15
18 h	37.0	25.8	48.6	37.4	48.4	44.1
3 d	61.1	49.4	56.8	54.7	54.1	54.2
28 d	72.0	72.5	66.2	70.9	65.1	68.0

Environmental impact of concrete

In practice, concrete contains coarse aggregates and less cement paste than mortar. For the present study the paste volume was fixed to 30.5 Vol.-% compared to 51.5

Vol.-% with which the mortars were prepared. Due to the higher cement paste volume of a cubic meter of 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 Mixtures M1&M15 are depicted in Figure 5. The percentages of M15 compared to M1 for concrete (mortar) are 72.0(69.1)% and 66.2(59.4)% for MKI and CO_2-emissions, respectively.

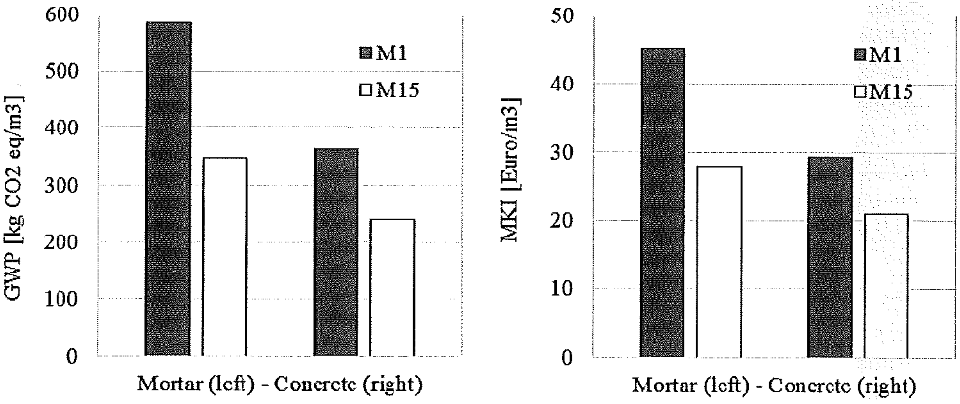

Figure 5. Global Warming Potential (a, left) and MKI (b, right) per cubic meter of the reference concrete/mortar (M1) and the slag concrete/mortar (M15)

Conclusions

An experimental study was executed with mortars and concretes in order to determine the potential for a reduction in environmental footprint by clinker replacement without compromising on the (early age) strength development. The environmental impact was quantified with the parameters relative strength cost, environmental impact factor MKI and CO_2-emissions. The following conclusions can be drawn:

- The replacement of OPC by fly ash at a replacement level of 30% decreased the compressive strength at 18 hours and 28 days. The compressive strength of an OPC-limestone powder combination was similar at both ages for a limestone replacement of 10%; the highest strength relative to the reference mixture was obtained with a 20°C curing.
- In order to realise a significant reduction in environmental impact, ground granulated blast-furnace slag was tested as a cement replacing material. The addition of the hardening accelerator containing of CSH nanoparticles largely compensated the loss in early age strength and up to 35% of OPC could be replaced by blast-furnace slag.
- Concretes were produced at similar strength levels compared to an OPC-reference mixture with a reduction of about 30% in Global Warming Potential and environmental impact factor MKI. With regard to the relative strength costs, a reduction of more than 50% was obtained with some of the mixtures.

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