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A New Generation of Sustainable Structural Concretes – Design Approach and Material Properties

H S Müller¹, J S Moffatt², M Haist² and M Vogel¹

¹ Institute for Concrete Structures and Building Materials (IMB), Karlsruhe Institute of Technology (KIT), Gotthard-Franz-Str. 3, 76131 Karlsruhe

² Institute of Building Materials Science, Leibniz University Hannover, Appelstr. 9A, 30167 Hannover

harald.mueller@kit.edu, j.moffatt@baustoff.uni-hannover.de,
haist@baustoff.uni-hannover.de, michael.vogel@kit.edu

Abstract. Sustainable concretes, also termed eco-concretes or green concretes, produced with a significantly reduced cement content provide a promising alternative for improving concrete sustainability without using supplementary cementitious materials, such as fly ash or slag. However, the production of such eco-concretes is a challenge in view of concrete technology and concrete properties. In particular, new design concepts as well as new admixtures have to be developed and applied to produce concretes with a cement clinker content of approx. 100 kg/m³ while keeping the concrete performance on a level similar to ordinary structural concrete of today.

To evaluate the sustainability of these new types of concretes not only the very low ecological impact due to the composition may be regarded, but in addition also their technical performance, i.e. their mechanical, physical and chemical properties have to be taken into consideration.

This contribution firstly gives an overview on sustainable approaches for concrete structures, further introduces the Building Material Sustainability Potential as an index, which is applied in combination with the service life prediction for cement-reduced concretes using full probabilistic methods. The composition of these particular structural concretes is discussed and related test results for their performance are presented. The contribution closes with an introduction to graded concrete structures as an innovative approach for the improvement of concrete sustainability on a structural level and presents testing results for mechanical and durability properties of graded bending beams.

The paper at hand extends the information given in [1] by looking more closely at the performance of graded concrete structures and here in particular by considering concretes produced from intermixing two concrete types (i.e. eco-concrete and UHPC) in the fresh state.

1. Introduction

The building industry is affected by the ongoing sustainability debate more than any other industry, due primarily to the pronounced environmental impact resulting from the production of building materials, the erection of buildings and structures and the subsequent use thereof [2]. This holds especially true for concrete structures, as the production of this material – and here especially the production of the raw material cement – is highly energy intensive and the source of substantial emissions of CO₂ [3]. Reducing the environmental impact of concrete production independently of the resulting consequences for the performance and durability of the material, however, is inadequate. Since the required service life of concrete structures normally ranges between 50 to 100 years, the environmental impact from



concrete production is distributed over a long time period. Therefore, increasing the sustainability of building structures requires a reduction of the environmental impact associated with the building erection, maintenance and operation processes and a concurrent increase of the durability of the structures at their maximum technical performance. This relation is described in Eq. 1 (see also [4]).

$$\text{BMSP} = \frac{\text{Service Life} \cdot \text{Performance}}{\text{Environmental Impact}} \quad (1)$$

The BMSP is the so-called Building Material Sustainability Potential. Even though the definition given above differs from standard definitions of the term sustainability, it agrees well with the latter, addressing the three basic pillars of sustainability, i.e. environmental aspects (by introducing the environmental impact) as well as socio-economic aspects (contained in the service life and performance parameters). As socioeconomic aspects, however, are extremely difficult or even impossible to evaluate during the concrete development process (i.e. the mix design), the definition given in Eq. 1 provides engineers with a simple tool to quantify the advantages and disadvantages of a specific concrete type with regard to its potential as a sustainable material. The exploitation of this potential during the design and construction process depends on the designer and user of the building or structure.

According to Eq. 1, three basic approaches to a sustainable use of concrete exist: The first is the optimization of the composition of the concrete regarding its environmental impact while maintaining an equal or better performance and service life; the second is the improvement of the concrete's performance at equal environmental impact and service life; the third is the optimization of the service life of the building material and the building structure at equal environmental impact and performance. A combination of the above named approaches appears reasonable.

In this paper the sustainability of so-called eco-concretes, i.e. concretes with a strongly reduced cement content, is discussed. The principles and methods applied during the mix design of the presented concretes can be viewed in [4]. The focus of the paper at hand rather is placed on outlining the calculations related to the Building Material Sustainability Potential (BMSP) of these materials, see also [5], and on considerations regarding sustainability aspects on the structural level.

2. Materials

Following the approach of minimizing the environmental impact of concrete during the design phase, materials were selected with low environmental impact as judged by environmental impact indicators. Table 1 presents an overview of environmental impact indicator data representative of the materials used. The data in Table 1 demonstrate that the constituent material cement is critical for the environmental impact of concrete due to its high global warming potential (GWP). While the GWP of superplasticizers is similar to that of cement, it is of minor importance on account of the small dosages of this substance in concrete.

As binders for the eco-concrete investigations two cements, the first being a CEM I 52.5 R in accordance with [6] and the second being a micro-cement with strongly reduced particle size, were selected. Because no product specific life cycle analysis data were available for the CEM I 52.5 R binder, the available data in [7] for a CEM II 52.5 binder were chosen as representative for a wide range of Portland cement binders. Product specific life cycle inventory data also could not be collected for the micro-cement. Since the latter is produced by separating the fine particles from a CEM I 52.5 R, it is expected that the data will be very similar with slight increases due to increased grinding. The increase has been conservatively estimated by considering the grinding energy demand required to increase the Blaine value from 5800 to 6900 cm²/g (see Table 2) on the basis of data provided in [8] for a ball mill, resulting in an energy demand of 0.0245 kWh/kg. Hereby it is assumed that the grinding is carried out by electrical energy input. Considering the German energy mix with specific CO₂ emissions of 0.56 kg CO₂/kWh (see [9]) the additional CO₂ emissions amount to approximately 0.0147 kg CO₂/kg cement, an increase of 1.6 % against the CEM II 52.5 data presented in [7]. The additional primary energy consumption for the micro-cement was allocated with 25.9 % renewable energy according to data in [9] for 2014. The consideration of further environmental impact indicators was neglected.

Table 1. Typical life cycle inventory data for cements and inert granular concrete constituent materials

Material	Primary energy consumption		Global Warming Potential GWP [eq. kgCO ₂ /kg]	Ozone Depletion Potential ODP [eq. kgR11/kg]	Acidification Potential AP [eq. kgSO ₄ /kg]	Eutrophication Potential EP [eq. kgPO ₄ /kg]	Photochem. Ozone Creation Potential POCP [eq. kgC ₂ H ₄ /kg]	Sources
	Non-renew.	Renew.						
	[MJ/kg]							
Cements								
CEM II 52.5	2.735	0.435	0.871	1.119·10 ⁻¹¹	1.108·10 ⁻³	1.213·10 ⁻⁴	1.445·10 ⁻⁴	[7]
Micro-cement (μCEM)	2.800)	0.459	0.885	1.119·10 ⁻¹¹ *)	1.108·10 ⁻³ *)	1.213·10 ⁻⁴ *)	1.445·10 ⁻⁴ *)	see text
Micro-silica	Detailed data are unavailable; the environmental impact was neglected in calculations in accordance with the reasoning in [10]							
Stone powders and aggregates								
Quartz powders	2.119	0.7407	0.1203	n/a	4.1·10 ⁻⁴	n/a	n/a	[11]
Sand 0/2	7.044·10 ⁻³	4.057·10 ⁻²	2.955·10 ⁻³	1.520·10 ⁻¹³	8.965·10 ⁻⁶	1.757·10 ⁻⁶	-1.055·10 ⁻⁷	
Gravel 2/8 and 8/16	7.044·10 ⁻³	4.057·10 ⁻²	2.955·10 ⁻³	1.520·10 ⁻¹³	8.965·10 ⁻⁶	1.757·10 ⁻⁶	-1.055·10 ⁻⁷	[7]
Superplasticizer (PCE based)	27.95	1.20	0.944	3.29·10 ⁻⁸	1.19·10 ⁻²	5.97·10 ⁻³	5.85·10 ⁻⁴	[12]
Water	1.22·10 ⁻³	4.2·10 ⁻⁴	2.56·10 ⁻⁴	n/a	n/a	n/a	n/a	see text

*) the influence of increased fineness through the grinding process has been neglected
n/a not available

A micro-silica powder was included to study the influence of the interfacial transition zone (ITZ) in the durability investigations, however, on account of the very limited availability of this material it is generally not recommended as a constituent material in cement-reduced concrete. As the availability of supplementary cementitious materials, e.g. fly ash or blast furnace slag, may decline relative to future concrete demand, no further supplementary cementitious materials were included in this research.

Coarse and fine aggregate fractions consisting of gravel and sand fractions and inert quartz powders were selected to make up the majority of the solid material in the granular matrix of the concretes. Selected properties of the cements and inert materials used are presented in Table 2.

Table 2. Properties of cements and inert aggregates investigated

Reactive components							
Property	Dimension	CEM I 52.5 R		Micro-cement		Micro-silica	
Density [13]	[g/cm ³]	3.117		3.110		2.225	
Blaine value [14]	[cm ² /g]	5800		6900		-	
BET [15]	[m ² /g]					22.9	
Time of initial set [16]	[min]	170 ¹⁾		77		-	
Compressive strength f _{c,28d} [17]	[MPa]	68.0 ¹⁾		106.3		-	
Inert aggregates							
Property	Dimension	Quartz powder 1	Quartz powder 2	Sand 0.1/1 mm	Sand 1/2	Gravel 2/8 mm	Gravel 8/16 mm
Density [13, 18]	[kg/dm ³]	2.64	2.65	2.65	2.65	2.63	2.65
Water absorption [18]	[m.-%]	-	-	0.2	0.3	1.8	1.5
Blaine value [13]	[cm ² /g]	18.000 ¹⁾	1.500	-	-	-	-

¹⁾ Data supplied by producer

The particle size distribution of the mixture of granular constituents was optimized using the CIPM-Model by Fennis [19] and adjusted to yield mixes with maximum packing density and minimum voids content. A detailed description of this procedure can be found in [4, 20].

3. Composition of the Investigated Concrete Mixes

Based on the raw materials detailed above, six different concrete mixes with cement contents ranging between 4 vol.-% and 10 vol.-% of the total solid particles volume were developed. The composition and selected properties of the mixes are detailed in Table 3.

The mix design process consisted of the following steps: Firstly, the raw materials of the concrete were selected with the objective of minimizing the content of materials with pronounced environmental impact within the concrete mixture. Secondly, the cement content within the concrete was defined as a volume fraction of the total solid particles volume contained in the mixture. Each mixture contained only one cement, either the CEM I 52.5 R or the micro-cement. Thirdly, the volume content of each inert granular constituent material was adjusted to maximize the packing density of the solid particles in the fresh concrete while taking into account the influence of cement particles on the packing density. The particle packing model CIPM (Compaction Interaction Packing Model) by Fennis [19] was used to judge the particle packing density while adjusting the granular mixture composition.

Finally, the fresh concrete properties of the mixtures were optimized by adjusting the water content in each mixture. Each mixture was provided with a PCE-based superplasticizer according to the recommendations made in [19].

The composition of the mixes detailed in Table 3 is characterized by cement contents between 109 kg/m³ to 268 kg/m³, compared to a cement content of 320 kg/m³ in the reference mixture. Additionally, in one mixture the cement CEM I 52.5 R was combined with micro-silica by replacing 5 % by mass of the cement by the corresponding mass of micro-silica (referred to as SF-CEM I). Hereby the effect of an improvement in the quality of the interfacial transition zone was studied. The 10 vol.-% mixture was adjusted to have an effective w/c-ratio of 0.43 with a cement content corresponding to the minimum requirements of EN 206-1 [21]. Details regarding the mixture development process can be found in [20].

4. Properties of the Investigated Concrete Mixes

The fresh concrete was tested for its compactability *c* according to [24] or its spread value *a* according to [25], depending on the flow characteristics of each mixture. Specimens were cast and subsequently demolded at the age of 2 days, cured in water until the age of 7 days and stored at 20 °C and 65 % r. h. until the age of 28 days. The compressive strength of the samples was tested according to [26]. The corresponding results are detailed in Table 3 and show that the investigated concretes provide high compressive strengths despite relatively high w/c-ratios, which could indicate an effect of the densely packed granular structure on the performance of the concretes. The performance levels exceed the demands for most common applications. A slight drawback regarding the workability of the cement-reduced mixtures can also be observed in Table 3, as with decreasing cement content the flow value decreases from 480 to 390 mm. Below 5 vol.-% of cement in the dry mix it is no longer measurable and must be supplemented by measurement of the degree of compactability *c*. This indicates a necessity for improvement of the workability properties of cement-reduced concretes with cement concentrations lower than 6 vol.-% of the solid particles volume in the mix.

The environmental impact of each concrete is represented here by its Global Warming Potential (GWP) and has been calculated based on the life cycle inventory data and content of each raw material as specified in Tables 1 and 3. A marked reduction in the Global Warming Potential can be observed between the mixtures containing 10 vol.-% and 4 vol.-% cement in the dry mix, nearly halving the Global Warming Potential from 259 kg CO₂/m³ to 136 kg CO₂/m³. All mixtures lie significantly below the reference concrete with a Global Warming Potential of 284 kg CO₂/m³.

Table 3. Mixture composition and properties of the developed concretes

Raw material / characteristic value	Dimension	Concrete mixture						
Mixture parameters								
Cement content in dry mix	[vol.-%]	4.0	4.0	4.0	5.0	6.0	10.0	Reference [22, 23]
Cement type	[-]	CEM I 52.5 R	μCEM	SF-CEM I	CEM I 52.5 R	CEM I 52.5 R	CEM I 52.5 R	CEM I 42.5 R
Mixture composition								
Cement	[kg/m ³]	113	111	109	138	162	268	320
Quartz powder ¹⁾	[kg/m ³]	216	217	216	212	161	141	-
Sand (0–2 mm) ¹⁾	[kg/m ³]	953	955	954	914	912	877	550
River gravel (2–16 mm) ¹⁾	[kg/m ³]	988	990	988	966	945	941	1277 ⁴⁾
Water	[kg/m ³]	87	85	87	106	126	130	192
Superplasticizer (PCE based)	[kg/m ³]	6.5	6.4	6.5	6.0	5.7	6.2	-
w/c-ratio	[-]	0.64 ²⁾	0.64 ²⁾	0.65 ²⁾	0.67 ²⁾	0.69 ²⁾	0.43 ²⁾	0.60
Concrete properties with investigation method								
Degree of compactability c [24]	[-]	1.25	1.21	1.19	-	-	-	n/a
Spread value a [25]	[mm]	-	-	-	390	450	480	n/a
Mean compressive strength $f_{cm,28d}$ [26]	[MPa]	76.9	79.0	76.6	69.8	58.2	102.6	38.4
Characteristic compressive strength $f_{ck,28d}$ ⁶⁾	[MPa]	68.9	71.0	68.6	61.8	50.2	94.6	30.4
Carbonation depth d (accelerated conditions acc. to [27]) mean / SDV	[mm]	5.8 / 2.3	0.8 / 1.3	5.2 / 1.4	7.2 / 2.1	8.7 / 2.7	- / -	4.9 / -
Inverse carbonation Resistance R_{ACC}^{-1} Mean / SDV	[(10 ⁻¹¹ m ² /s)/ (kgCO ₂ /m ³)]	18.9 / 6.8	0.4 / 0.3	14.7 / 5.6	29.6 / 9.8	42.9 / 13.0	- / -	13.4 / 3.1
Calculated technical life span with $\beta = 1.3$ under carbonation attack (t_{st}) (see Fig. 4)	[a]	85	200	106	55	36	200	118
Global Warming Potential (GWP)	[kgCO ₂ /m ³]	136	136	133	157	171	259	284
Building Material Sustainability Potential (BMSP)	[MPa·a/kg CO ₂]	43	104	55	22	11	73	13

¹⁾ oven-dry

²⁾ water absorption of the aggregate has been taken into account; compare Tab. 2

³⁾ estimated using life cycle assessment data presented in Tab. 1

⁴⁾ no information was available for the aggregate distribution; aggregate masses of the reference concrete were estimated as follows: 1.5 vol.-% air content with a distribution of aggregates with 30 vol.-% sand 0–2 mm, 35 vol.-% gravel 2–8 and 35 vol.-% gravel 8–16 representing an AB16-distribution curve [28].

⁵⁾ prediction of functional life span limited to 200 years (see text)

⁶⁾ $f_{ck,28d} = f_{cm,28d} - 8$ MPa

Besides the concrete properties in the fresh state and the mechanical properties, the concretes were also tested for their durability under common environmental exposure conditions such as freeze-thaw attack with de-icing salt, carbonation and chloride ingress. Experimental results of the carbonation experiments served in the calculation of the service lifetime expected of these new concretes which are also presented in the following.

Fig. 1 shows the results of capillary suction tests and freeze-thaw tests conducted according to the CDF-method as described in [29] and [30]

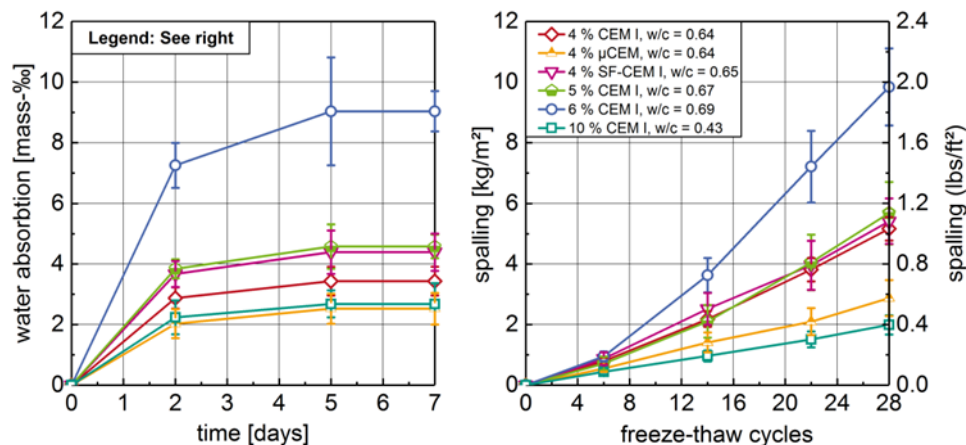


Figure 1. *Left:* Measured capillary suction while in the capillary suction bath. *Right:* Concrete spalling of investigated mixes in the CDF-test according to [29] and [30]

As can be seen from the results detailed in Fig. 1, neither the concrete tested with 10 vol.-% cement content, corresponding to 268 kg/m^3 , nor the concretes with reduced cement content fulfilled the requirements for a concrete corresponding to exposure class XF4 (high water content with chloride attack) according to [28] with a maximum allowable mean value of spalling of 1500 g/m^2 (0.307 lbs/ft^2) of the surface under attack according to [29]. For the cement-reduced mixtures, this result was expected. In the case of the 10 vol.-% mixture with an effective w/c-ratio of 0.43, the displayed behavior may be a result of increased capillary suction resulting from a shift of the capillary pore structure toward finer capillary pores on account of the fine quartz powders embedded within the hardened cement paste. Despite its significantly higher w/c-ratio of approximately 0.63, the mix containing 4 vol.-% of micro-cement exhibited a similar, though slightly inferior, freeze-thaw resistance compared to the concrete with a cement content of 10 vol.-% and an effective w/c-ratio of 0.43, which is possibly the result of a higher degree of hydration of the micro-cement. However, the experimental data also show that the capillary suction and the freeze-thaw resistance of mixes with 4 vol.-% of cement show lower water absorption and a lower spalling than mixes with cement contents of 5 and 6 vol.-% with similar w/c-ratio. This result can be explained by the reduced surface area of hardened cement paste per unit area of concrete under attack as the cement content is reduced, when additionally considering the declining performance of mixes with increasing cement content. Since only the hardened cement paste is susceptible to a freeze-thaw attack, this effect obviously offsets in part the detrimental effect of an increased w/c-ratio. Unfortunately, the amount of data available is still too small to derive a general law which quantifies both effects.

In order to investigate the influence of the interfacial transition zone (ITZ) on the durability of concretes with low cement content, in the mix designated “4 % SF-CEM I” 5 % by mass of the Portland cement were replaced by a micro-silica. It was dosed to the coarse aggregates prior to mixing in order to enhance a localization of these particles on the coarse aggregate surfaces. The comparison of this mix with the corresponding mixture without micro-silica, i.e. the mix containing 4 vol.-% of Portland cement, does not show any difference in the freeze-thaw behavior. Here it appears the w/c-ratio of the cement

matrix is generally too high for the ITZ to have any significant effect on the freeze-thaw resistance. Small differences, however, become apparent when comparing the results of the water absorption test. Here, the mix containing micro-silica exhibits higher water absorption than the mix without micro-silica.

A very important aspect in the evaluation of the durability of the investigated concretes is their resistance against a CO₂-induced carbonation. To test this, two beam-shaped samples per mixture with dimensions of 100 x 100 x 440 mm³ were cast, demoulded after 2 days and stored under water at 20 °C until the age of 7 days. Then the beams were removed from water storage and exposed to dry conditions at 20 °C and 65 % r. h. until the age of 28 days. At this age, half of the beams were removed from the climate chamber and exposed to an increased CO₂ concentration of 2 vol.-% at 20 °C and approximately 70 % r. h. Both the samples carbonating under normal and under increased CO₂ concentration were investigated for their carbonation depth at the age of 56 days by splitting the samples into slices at four points along the length axis of each beam and applying phenolphthalein to the surfaces of the freshly exposed cross sections. The carbonation depth of each concrete under normal and accelerated conditions was determined by measuring inward from the outer edge at 3 points from each of the 4 edges of the slices. The mean value of the carbonation depth was formed for each beam out of the resulting 48 measurements taken. The results are presented in Fig. 2.

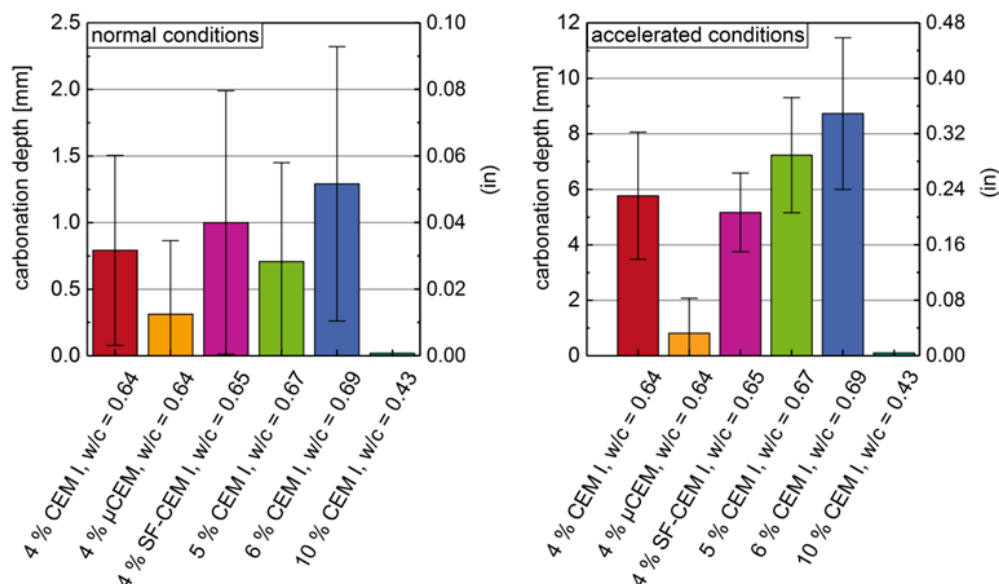


Figure 2. *Left:* Carbonation depth of concretes at 56 days of age exposed to natural CO₂ environment at 20 °C and 65 % r. h. *Right:* Carbonation depth of the concrete at 56 days of age in 2 vol.-% of CO₂ at 20 °C and approximately 70 % r. h. (for test procedure see the text)

As can be seen from Fig. 2 (left), the 10 vol.-% concrete (w/c = 0.43) subjected to normal carbonation (i.e. approximately 0.04 vol.-% of CO₂) does not show any carbonation at all, whereas the samples with reduced cement content exhibit a significantly increased carbonation depth. The worst performance in this comparison was observed again with the mix containing 6 vol.-% of cement, followed by the mixes with 5 and 4 vol.-% cement. While the differences between the 6 vol.-% mix compared to the 4 and 5 vol.-% mixes are of statistical significance, the differences between the latter two are not. The same is true regarding the differences between the composite cement containing micro-silica and the corresponding mix without micro-silica. Similar results with regard to the ranking of the performance of the investigated concretes can be found for the samples exposed to an accelerated carbonation at 2 vol.-% of CO₂ in Fig. 2 (right). In this test setup the 10 vol.-% concrete also did not exhibit any carbonation. The best performance of all cement-reduced concretes was found for the mix with 4 vol.-% of micro-cement.

In order to investigate the chloride migration behavior of the concretes, the rapid chloride migration test (RCM) according to [31] was performed. For this test, cylinders with a height of 300 mm and a diameter of 100 mm were cast, demoulded after two days and cured submerged under water at 20 °C until the age of 28 days. In the week before testing, discs 50 mm ± 5 mm in height to be tested with the RCM-apparatus were extracted by saw from each cylinder.

Results of the testing are presented in Fig. 3. The chloride migration coefficients confirm the strong influence of cement paste content on durability properties of the concrete. Again, with decreasing cement content in the dry mix and a similar w/c-ratio the durability characteristics in the concrete improve. This is especially evident when comparing the mix with 6 vol.-% of cement in the dry mix to the mixtures with 4 vol.-%. The mixture with micro-cement again displays the best characteristics of any cement-reduced concrete mixture. In this case it is especially noteworthy that the cement-reduced mixture with micro-cement exceeds even the durability characteristics of the 10 vol.-% mixture with an effective w/c-ratio of 0.43. This may be a result of the advanced degree of hydration of the mixture with micro-cement and differences in the chemical makeup between the two clinker types. The mixture containing micro-silica showed no advantage over the comparable cement-reduced mixture with Portland cement.

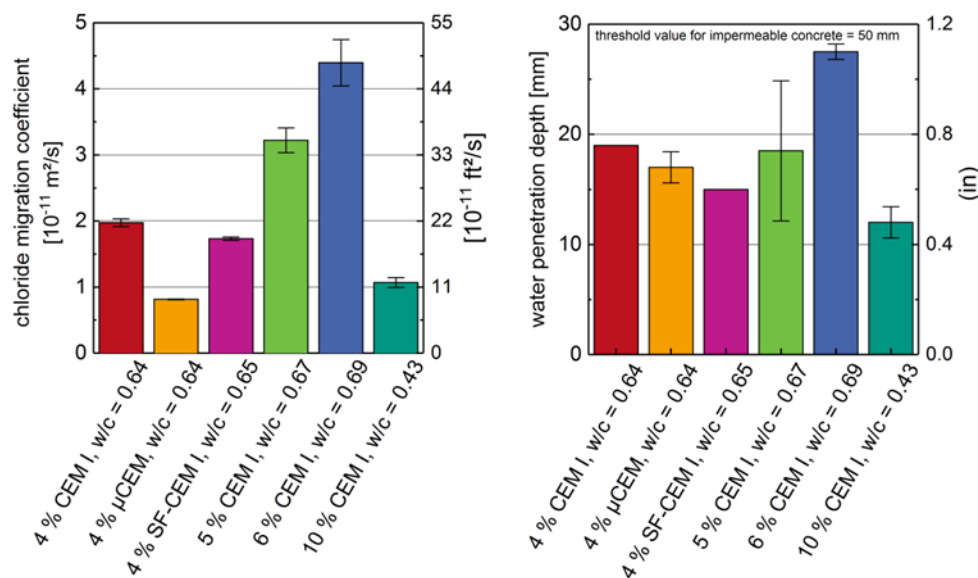


Figure 3. *Left:* Chloride migration behavior measured by the RCM-method [31]. *Right:* Water penetration depth measured according to the procedure in [32]

Fig. 3 also displays the results of the water penetration depth determined under pressure, measured according to [32]. In this case, all investigated concretes meet the threshold value for impermeable concrete, the 10 vol.-% mixture having the lowest penetration depth. Here, also, the trend of lower cement paste content improving the concrete resistance against permeation can be observed among cement-reduced mixtures.

5. Service Life Design as a Key to Sustainable Buildings and Structures

As illustrated by Eq. 1, maximizing the service lifetime of a building or a structure is a very efficient way to improve the sustainability of our built environment. Methods to predict the service life of a concrete structure and to design the structure accordingly are essential tools in the sustainability assessment process for sustainable buildings and structures. However, this aspect is often neglected in the current life cycle assessment debate, leading to a one sided focus on a pure reduction of environmental impact while neglecting the durability and thus the sustainability of the designed structures. As for the limit state, a concrete cover of 40 mm with a standard deviation of 8 mm was

chosen. The target reliability $\beta_{\text{target}} = 1.3$ was chosen to be 1.3. The procedure of service life prediction by means of the carbonation process applied to green concretes and the reference concrete presented is described in detail in [33]. Here only the final results of the service life predictions are presented.

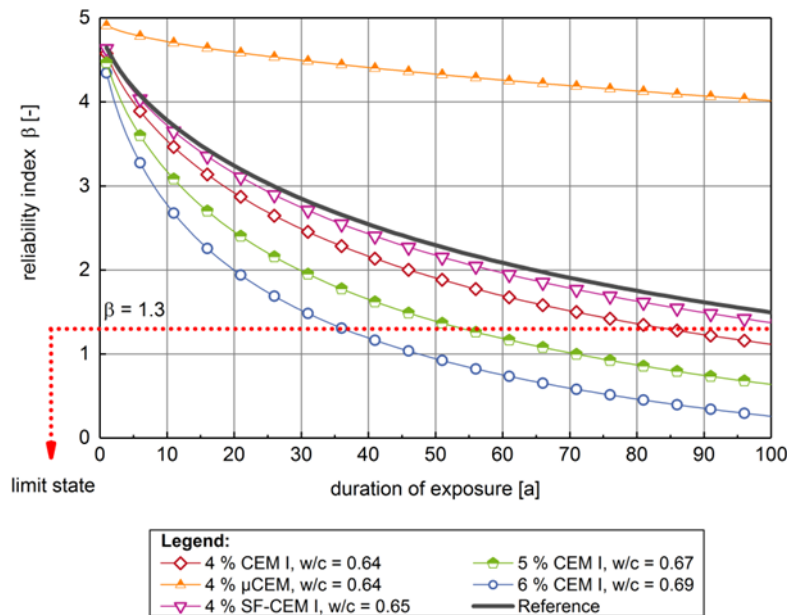


Figure 4. Comparison of exemplary service life predictions between developed green concretes and a normal concrete (reference) taken from literature data [22, 23]

The reference concrete reaches the chosen target reliability index of $\beta_{\text{target}} = 1.3$, the acceptance criterion, after 118 years, while the cement-reduced mixtures with between 6 vol.-% and 4 vol.-% cement contents in the dry mix fall short of the reference mixture. On account of the good carbonation resistance displayed by the mixture containing micro-cement in the accelerated test, the calculated reliability curve for this concrete lies exceptionally high, indicating limitations to the testing and prediction method to be considered during the process. Also, on account of the mixture with 10 vol.-% cement in the dry mix showing no carbonation under accelerated conditions, a service life prediction could not be performed for this mixture. In both cases, the service life has been generously capped in the following consideration at a theoretical maximum of 200 years for these exposure conditions and the reasons stated. Combining the measured life cycle assessment data and the performance properties of the green concretes with the durability parameters determined by experiment and the resulting probabilistic service life predictions, it is now possible to evaluate the Building Material Sustainability Potential (BMSP) as described in Eq. 1. The results are shown in Fig. 5.

It can be seen in Fig. 5 that all cement-reduced concrete mixtures exceed the reference mixture in terms of BMSP with exception of the mixture containing 6 vol.-% cement in the dry mix. This mixture would generally be excluded from most uses on account of its predicted service life of less than 50 years under carbonation attack (see Fig. 4). In this case the mixture containing only 4 vol.-% micro-cement in the dry mix, corresponding to 111 kg/m^3 , has the most sustainability potential, provided its technical performance and predicted service life can be fully exploited.

Examining Fig. 5, it should be noted that the proposed Building Material Sustainability Potential (BMSP) indicator has no physical meaning but serves the concrete technologist during the planning process. It is intended to illustrate in quantifiable terms the advantages and detriments as a consequence of measures taken to reduce concrete's environmental impact and contribute to its sustainability during the mix design. The functional relation of the BMSP is currently still very simple, but may be further developed to better reflect the significance of each parameter with regard to the material sustainability, appropriately weighting the parameters and their interdependence. Also, further parameters reflecting restrictions in constituent material availability may be introduced in the future.

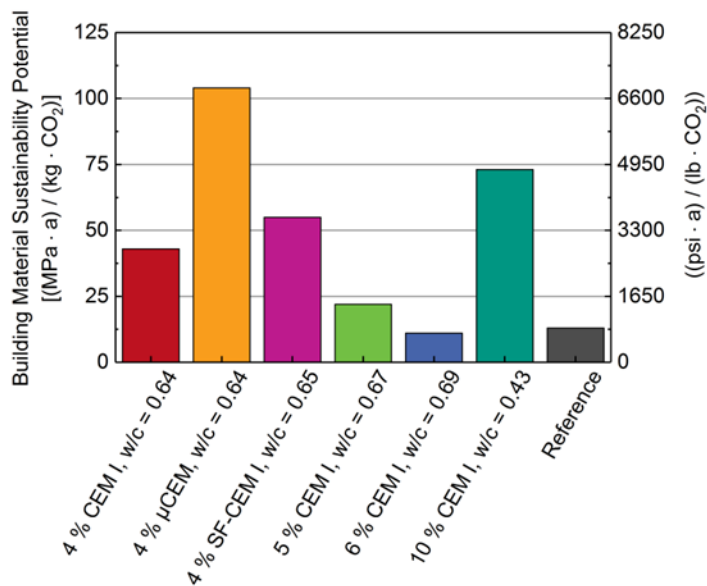


Figure 5. Building Material Sustainability Potential (BMSP) acc. to Eq. 1 of the developed cement-reduced concretes compared to the reference concrete from literature (see Table 3)

6. Sustainability of Graded Concrete Structures

Potential for the improvement of the sustainability of concrete structures lies not only on the material level, but extends to the structural scale also. Graded concrete members will in the following be discussed as an innovative approach. For this purpose, selected results from investigations performed in [34, 35] will be presented. Graded structures are structures in which the mechanical, physical or chemical properties of the material are adjustable within the structural geometry to satisfy precisely the predominant requirements in each location. In the following, the principal of graded concrete members is presented and discussed by the example of stratified, reinforced concrete bending beams, in which the concrete properties are adjusted over the depth of the cross section. Such beams can be produced by placing layers of different fresh concretes upon one another. The objective is, in this case, to reduce the environmental impact of the bending beams without impairing their load bearing behavior and durability properties. The environmental impact considered here is the Global Warming Potential from the constituent materials.

In the first step, two so-called root mixtures were designed: The first mixture was identical to the concrete detailed in Table 3. The second root mixture was fiber-reinforced UHPC with ca. 600 kg/m³ of a CEM I 42.5 R, 157 kg/m³ of micro-silica powder, 189 kg/m³ of water, 28 kg/m³ of superplasticizer, 1344 kg/m³ of quartz powder and sand and 160 kg/m³ of steel fibres (GWP = 1018 kg CO₂-eq/m³). Cross sections of reinforced bending members to be tested in 4-point bending tests were designed from these mixtures in which the root mixtures UHPC was designated for the tensile zone to protect the reinforcement through its strong durability properties and crack width limitation. From here on upward, as the level of tensile bending stress in the cross section decreases, the cross sections are graded toward an eco-concrete strong in compressive strength and low in environmental impact. The gradation is achieved by producing two further concretes, derived from the root mixtures, by mixing the root mixtures together in a separate mixing step in two volumetric combinations, 15/85 vol.-% and 50/50 vol.-% UHPC/Eco-concrete respectively. These additional mixtures, referred to in the following as derivative mixtures, are then placed in between the root mixtures in layers of varying thickness to produce gradual transitions across the height of the beams. Figure 6 presents the results of the mechanical characterization of the root concrete mixtures and derivative concrete mixtures.

As can be seen from Figure 6, which shows the performance properties as a function of UHPC content in the mixtures, the UHPC root mixture (100 vol.-% UHPC content) outperforms the eco-concrete (0 vol.-% UHPC content) in all cases. As the UHPC root mixture is introduced into the eco-concrete root mixture with 15 vol.-%, the mechanical performance of the derivative mixture (15 vol.-% UHPC content) increases as compared to the eco-concrete. A further increase of the UHPC content in

the derivative mixture to 50 vol.- results in a further improvement of mechanical performance in the derivative mixture (50 vol.-% UHPC content). Interestingly, at 50 vol.-% UHPC content the level of performance of the derivative mixture exceeds that of the root UHPC mixture. This was not necessarily expected, but may indicate a positive contribution of the granular aggregate structure of the eco-concrete to the performance of this derivative mixture. Most surprising in this regard was the high level of flexural tensile strength in the derivative mixture with 50 vol.-% UHPC content, which exceeds that of the UHPC root mixture's tensile strength in spite of having a lower content of steel fibers.

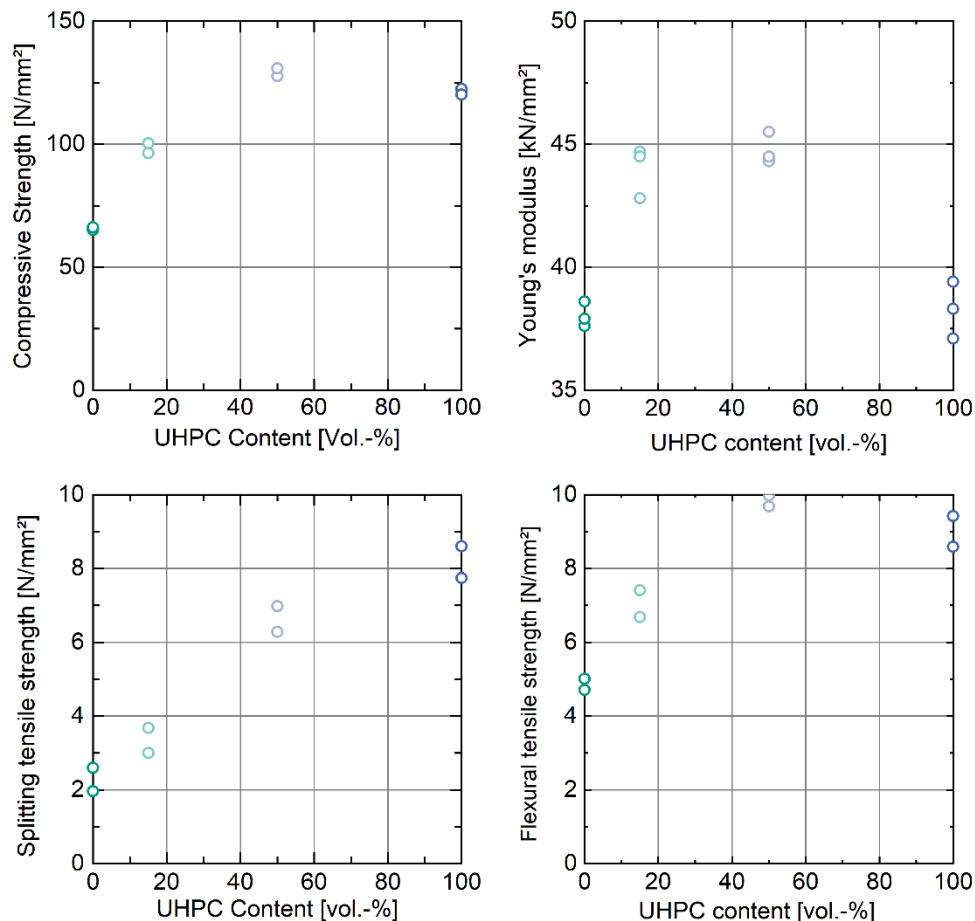


Figure 6: Mechanical properties of root concrete mixtures (eco-concrete, UHPC) and derivative concrete mixes (15/85 vol.-% and 50/50 vol.-% UHPC/eco-concrete). *Top Left:* Compressive strength tested according to the method in [26]. *Top Right:* Young's Modulus tested according to the method in [36]. *Bottom Left:* Flexural tensile strength tested according to the method in [37]. *Bottom Right:* Splitting tensile strength tested according to the method in [38]

In the second step, bending beams reinforced with 3 steel bars 8 mm in diameter tensile reinforcement and ca. 13 mm concrete cover were produced from the root mixtures and derivative mixtures. The first type of beam produced was a homogeneous cross section from each root mixture and each derivative mixture separately, see geometries A to D in Fig. 7 (left). The second type of beam consisted of cross sections which were graded in layers over their depth to investigate their load bearing behavior while attempting to minimize the Global Warming Potential. In this case, the eco-concrete root mixture was used to fill as much volume as possible to exploit its low Global Warming Potential mainly in the areas predominantly under compressive bending stress. The UHPC root mixture was used as sparsely as

possible on account of its high Global Warming Potential. The derivative concretes were used to form the stepwise transition between the UHPC and eco-concrete root mixture layers, resulting in cross sections with 3 and 4 layers. In all cases, only a fraction of the cement contained in the homogenous UHPC beams was used in the other homogeneous beams and the graded beams, see Fig. 7 (left).

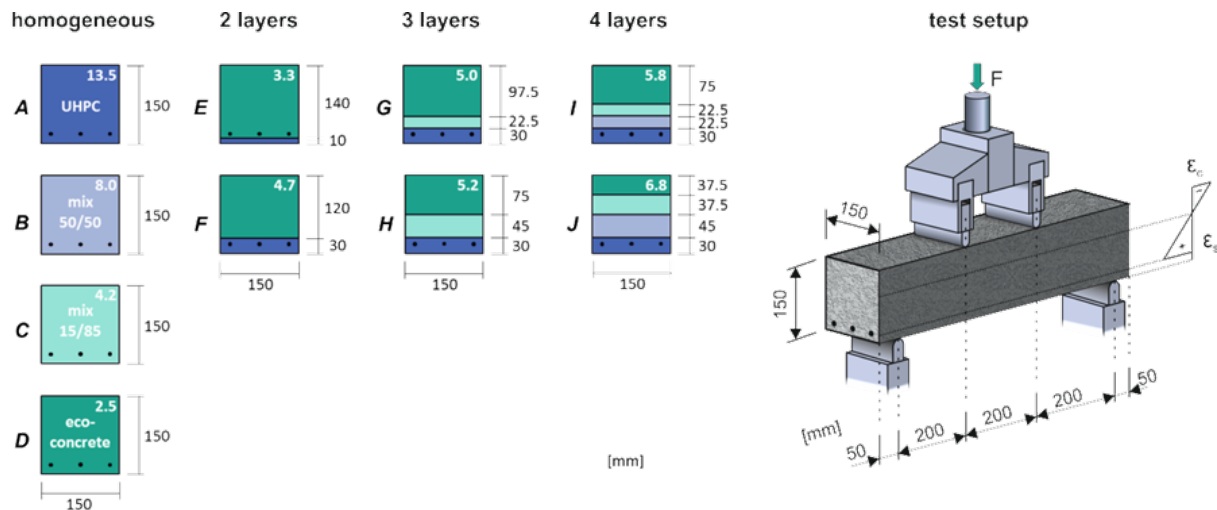


Figure 7. *Left:* Homogeneous and graded cross sections consisting of the root mixtures (UHPC and eco-concrete) and the derivative mixtures (15/85 and 50/50 vol.-% UHPC/eco-concrete). *Right:* Test-setup for 4-point-bending tests performed on each beam according to [37]

Fig. 7 (right) shows the test-setup in which the beams were tested according to [37] with a typical strain distribution used in dimensioning bending beams. Here, ϵ_c and ϵ_s denote the compressive and tensile strains respectively. Prior to each test, a load of 0.5 kN was applied to insure the loading yoke was securely pressed against the specimen. The specimen was then tested at a deformation rate of 0.1 mm/min until 0.75 mm deflection had been achieved, 0.125 % of the distance between the abutments. Thereafter, the testing speed was increased to 0.3 mm/min until at least 3.5 mm deflection, 2 % of the beam length, were reached. Fig. 8 shows the measured load-deflection curves of the homogeneous concrete beams (left) and the graded concrete beams (right). Two beams of each type were tested. The correspondence of the behavior between two beams of the same type appears generally very good.

Regarding the homogeneous beams, Fig. 8 (left) shows the eco-concrete beams have the lowest ductility, as cracking occurs the soonest and the curves begin to deviate from a quasi linear elastic behavior first. Following the onset of cracking, these beams are also the least stiff. The ductility, stiffness after cracking and maximum load bearing capacity of the homogeneous beams appear to increase with the content of fiber-reinforced UHPC in the mixture and are greatest in the beams containing strictly UHPC. This can be explained by the high compressive strength of the UHPC in combination with its high content of steel fibers. All beams behave in a ductile manner after failure on account of the steel reinforcement. While the beams consisting of the derivative mixture with 15 vol.-% UHPC content do not appear to significantly improve in performance over the homogeneous eco-concrete beams, the homogenous beams made of the derivative mixture containing 50 vol.-% UHPC do.

Fig. 8 (right) shows that all graded concrete beams improve in ductility, stiffness after cracking and maximum load bearing capacity when compared to the homogeneous eco-concrete beams, showing an improvement on account of the gradation measures taken. These properties furthermore appear to improve as the gradation of the beam becomes more diverse with an increasing number of layers of concrete. The beams consisting of four distinct layers, J and I specifically, nearly match the load-deflection behavior of the homogenous UHPC beams.

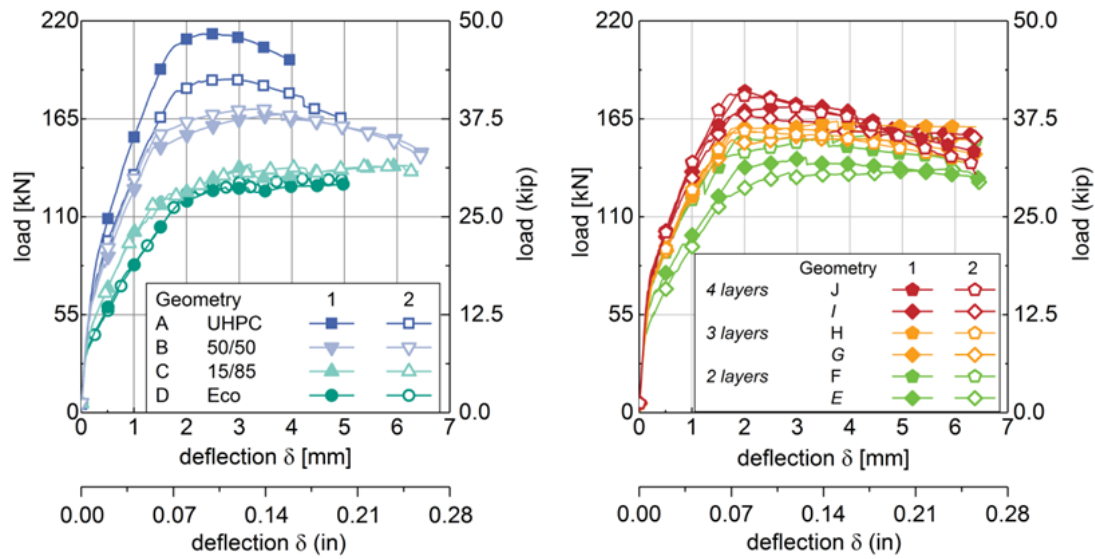


Figure 8. Load-deflection curves from 4-point-bending tests with reinforced bending beams. *Left:* Homogeneous beams. *Right:* Graded beams

In addition to the load bearing characteristics, preliminary durability investigations were performed. For this purpose, further beams were produced and loaded analogous to the methodology of the 4-point bending tests tests. The loading of the beams used here, however, was ended at 70 % of the failure load achieved during the mechanical tests, ensuring that tensile cracking had taken place but failure had not, reflecting the state of use for beams in practice. Subsequently, test specimens were extracted from the tensile zone in between the points of loading. The results of subsequent CDF-tests on such samples are presented in Fig. 9 [35].

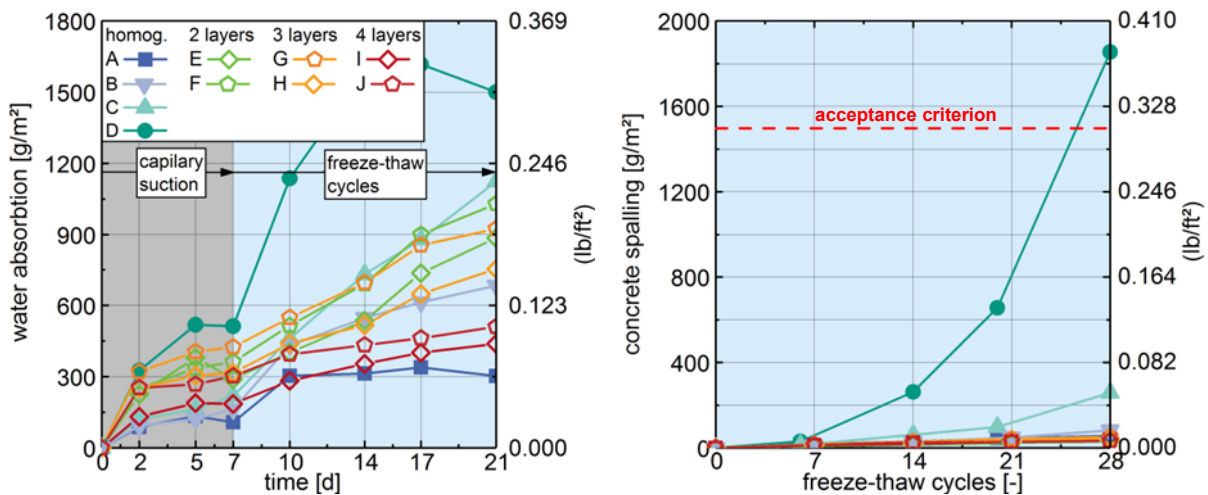


Figure 9. *Left:* Water absorption curves for test specimens extracted from damaged homogeneous and graded cross sections undergoing capillary suction and freeze-thaw attack. *Right:* Concrete spalling curves for the same specimens under freeze-thaw attack in the CDF-test

As can be seen in Fig. 9 (left) the water absorption curve during capillary suction and during the freeze-thaw attack lies highest for the homogenous specimens containing the eco-concrete root mixture which is a result of the comparatively high w/c-value in this mixture. As the UHPC content increases within

the specimens made from derivative mixtures, the water absorption decreases. The water absorption of the strictly UHPC specimen is only ca. 20 % of that of the eco-concrete specimen after both capillary suction and freeze-thaw attack.

Among the graded cross sections, the trend of an improving behavior with an increasing number of layers continues. While the curves for water absorption do not differ significantly between the specimens from cross sections with two layers and three layers (see geometries E, F, G and I) in which the bottom layers are UHPC and the layers above consist of the derivative mixture with 15 vol.-% UHPC content, the specimens from cross sections with 4 layers (see geometries I and J) improve significantly. In these, the layers above the UHPC consist of the derivative mixture with 50 vol.-% UHPC. This may be the result of improved cracking behavior in the cross sections and lower permeability on account of the higher performance of the concretes and higher fiber contents contained in the lower half of the cross sections. Figure 9 (right) shows, however, that while the eco-concrete shows significant spalling during the freeze-thaw attack, failing to meet the threshold value of 1500 g/m² according to [29], all other cross sections perform much better. The specimens consisting of the derivative mixture with 15 vol.-% UHPC content are second weakest in this comparison, but still lie far below the threshold value. It also appears that a thin layer of UHPC, not more than 10 mm, in the tensile zone is sufficient to significantly improve the freeze-thaw behavior of the eco-concrete specimens. It is unclear how pronounced the effect of the loading induced cracking was during the tests, as the tests were performed on the specimens after the load had been removed. Some crack healing, especially in UHPC layers, may have contributed to the behaviors observed. Refinement of the performance test methods in the laboratory will be necessary in the future to improve the interpretation of the results and enable probabilistic service life predictions for graded concrete members.

Fig. 10 presents the results of putting the Global Warming Potential of the beams, determined with the lifecycle data provided in Table 1, into relation with their load bearing capacity from the tests presented in Fig. 8. The result is an intensity of CO₂-emissions required to produce the load bearing capacity observed, given here as g CO₂-eq/kN. The advantage of concrete gradation with regard to sustainability can be seen here. The solid trend line of the homogeneous concrete beams is presented together with the dashed trend line of the graded concrete beams. The trend line of the graded beams lies significantly below the trend line of the homogeneous beams in this comparison, indicating an increase in the efficiency of the use of the binder cement as less CO₂-emissions are required to generate the load bearing capacity displayed. It appears possible with this combination of root concretes to reduce the CO₂-intensity of bending members by ca. 50% compared to homogeneous cross sections at high load bearing capacity. Further potential is also likely available in this regard. Exploiting it fully depends on the benevolent behavior of the durability properties of these members, which is still under investigation. Also, at this moment manufacturing techniques remain unconsidered.

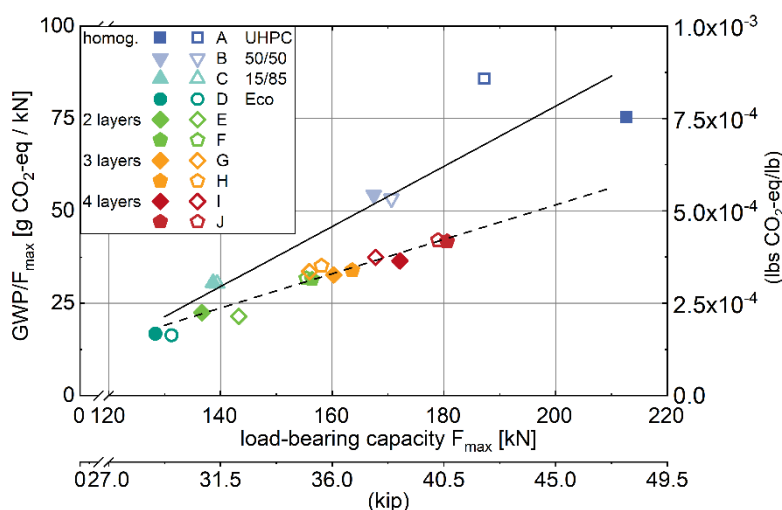


Figure 10. Evaluation of the sustainability of homogenous and graded concrete beams by comparison of the environmental impact (Global Warming Potential in [g CO₂-eq]) as a function of their mechanical performance (maximum load-bearing capacity in 4-point tests [kN])

7. Conclusions

The sustainability of concrete on the material level is difficult to quantify during the concrete mix design process, as the three interdependent parameters of performance, durability and environmental impact must be concurrently evaluated and optimized. The Building Material Sustainability Potential (BMSP) is thus introduced as a simple but suitable indicator for sustainability on a material level to assist during the mix design. It has been demonstrated that cement-reduced concrete can be produced while maintaining or even improving performance in compressive strength, provided suitable inert aggregates are available, raising potential for discussion of the current minimum cement contents within concrete standards. To evaluate the sustainability potential of the resulting concretes, however, their durability characteristics must also be considered.

Probabilistic service life design methods, relying on experiments and improved deterioration mechanism models, can be used to predict effectively the service life of concrete structures under defined environmental exposures. While experimental results indicate a deficit in the durability characteristics of cement-reduced concretes, this deficit may be insignificant depending on the intended exposure conditions. Due to significant increases in performance and strongly reduced environmental impact, the evaluation of the BMSP for at least one such concrete compared to a standard concrete indicates potential for a significant sustainability improvement when choosing the eco-concrete. Whether this benefit outweighs any potential drawbacks will also depend on the proper management of necessary maintenance measures when the service life of the structures finally expires.

Further potential to reduce the environmental impact of concrete structures can be realized by adapting the concrete properties to the local requirements in the structure, using high performance materials where necessary and environmentally friendly concretes where possible, within the same cross sections. This has been demonstrated for graded concrete bending members. Here, the environmental impact of bending beams could be reduced by approximately 50 % at high load bearing capacity by grading the structure between eco-concrete and UHPC, rather than producing homogeneous UHPC sections. Preliminary durability investigations appear promising that this method may be very effective to improve the durability of structures from eco-concretes also. Further investigations regarding the influence of concrete gradation of the mechanical behavior and durability behavior of graded structures are required in the future.

Beyond the achievements and potentials indicated above, it has to be faced that the production of eco-concretes, i.e. concretes with a cement or binder content of approx. 100 kg/m^3 (6.24 lb/ft^3) without further SCMs like fly ashes, blast furnace slags or others, presents new challenges. Firstly, the mix design process has to be developed further to make their production a matter of routine. This means on one hand that the available particle packing models have to be extended and improved, and on the other hand that new relations or prediction models, respectively, between the eco-concrete composition and the eco-concrete properties have to be developed. As an example, it is mentioned that the well-established Walz-curves (or Abram's law) no longer necessarily apply for eco-concretes. Furthermore, a new generation of adequate concrete admixtures must be developed to provide admixture interaction with inert constituent materials, despite strongly reduced water content, comparable to the interaction of current admixtures primarily with the cement or binder in the plentiful presence of mixing water. The current lack of such admixtures causes workability problems, for example, which have to be overcome before eco-concrete may be applied in practice on a routine basis. Corresponding research is under way.

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