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Design, material properties and structural performance of sustainable concrete

Harald S. Mueller[a], Michael Haist[a,*], Jack S. Moffatt[a], Michael Vogel[a]

[a]*Institute for Concrete Structures and Building Materials, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany*

Abstract

Green concretes, also termed eco-concretes, with reduced cement content may provide an alternative for improving concrete sustainability independently of used supplementary cementitious materials. However, to evaluate the sustainability of these new types of concretes not only the ecological impact due to the composition may be regarded but in particular also their technical performance, i.e. their mechanical, physical and chemical properties, have to be taken into consideration. Consequently, this paper introduces first the index Building Material Sustainability Potential, which is applied in combination with the service life prediction for cement-reduced concretes using probabilistic methods. Moreover, the composition of green concretes is indicated, and related test results on the performance of green concretes are presented. The potential of green concrete for applications in practice is shown by the structural performance of graded concrete members being loaded in flexural tests.

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Keywords: sustainability; graded concrete; green concrete; service life design; reliability

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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 [1]. 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 CO_2 resulting from the production process [2].

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* Corresponding author. Tel.: +49 (0) 721 608-42277; fax: +49 (0) 721 608-47796.
E-mail address: michael.haist@kit.edu

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There are different approaches to mitigating the emissions of CO_2 associated with the use of structural concrete in view of its composition. Besides the partial replacement of Portland cement clinker by supplementary cementitious materials or new types of binders, a very efficient and promising approach consists in a tremendous reduction of the cement (binder) content of the concrete. However, this only leads to a truly sustainable concrete if the resulting performance of this cement-reduced concrete, i.e. its mechanical, physical and chemical properties, may be kept almost identical compared to ordinary structural concrete. This means that for the evaluation of the sustainability of these new types of concretes not only the ecological impact due to the composition may be regarded but in particular also their technical performance.

Against this background the paper at hand introduces first the index Building Material Sustainability Potential, which takes into consideration the environmental impact of the concrete and its constituent materials, the performance of the concrete and its service life. Eco-concretes, also termed green concretes, have been produced and test results for the performance of these concretes are given. The development principles applied during the mix design procedures of the presented concretes are explained elsewhere, see [3]. The focus of the paper at hand rather is placed on outlining the calculations related to the Building Material Sustainability Potential (BMSP). Nevertheless, flexural tests on concrete beams are additionally shown, indicating very promising results if a grading with different concrete types including eco-concrete is applied.

2. Definition of the building material sustainability potential

To evaluate the sustainability of new types of concrete (green concrete) it is inadequate to consider just the prevention of CO_2 emissions being achieved e.g. by the partial replacement of Portland cement clinker by supplementary cementitious materials. It is necessary also to take into consideration at least the performance of the material and its service life.

Since the required service life of concrete structures normally ranges between 50 to 100 years, their environmental impact is spread over a long time period. From this it is evident that the sustainability of the concrete increases with increasing service life. Further, the sustainability of building structures requires a reduction of the environmental impact associated with the material, erection, maintenance and operation processes and a concurrent increase of the strength and durability of the materials and structures, respectively, at their maximum technical performance. These interactions may be expressed by means of Eq. 1 (see also [4]).

$$\text{Building Material Sustainability Potential (BMSP)} \sim \frac{\text{Service Life} \cdot \text{Performance}}{\text{Environmental Impact}} \tag{1}$$

Even though the definition given above differs from standard definitions of the term sustainability, it is well in line with the latter, addressing the three basic pillars of sustainability – i.e. environmental aspects (by introducing the environmental impact) as well as social and economic aspects (hidden in the service life and performance parameters). As social and economic 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.

It must be noted that all three parameters included in Eq. 1 are rather complex and may depend on the composition and interdependence of further parameters. For example, performance may be considered as the strength or the deformation characteristics as well as in terms of characteristics related to durability. The latter is a function of various physical and chemical attacks, which are certainly interrelated. Moreover, Eq. 1 connects the three parameters linearly, and no special weighting is applied to any of these parameters. However, for the time being it is neither possible nor reasonable to display Eq. 1 in a more complex way. This may be done when further research results justify extensions of this approach.

According to Eq. 1, three basic approaches to a sustainable use of concrete exist: 1st is the optimization of the composition of the concrete regarding its environmental impact while maintaining an equal or better performance and service life; 2nd is the improvement of the concrete's performance at equal environmental impact and service life; 3rd is the optimization of the service life of the building material and the building structure at equal environmental impact and performance. Finally, a combination of the above named approaches seems reasonable.

3. Investigated raw 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

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

Material	Primary energy consumption		Global Warming Potential **GWP** [kg CO_2 /kg]	Ozone Depletion Potential **ODP** [kg R11 /kg]	Acidification Potential **AP** [kg SO_4 /kg]	Nutrification Potential **NP** [kg PO_4 /kg]	Photochem. Ozone Creation Potential **POCP** [kg C_2H_4 /kg]	Source
	Non-renew. [MJ/kg]	Renew. [MJ/kg]						
Cements								
CEM I 32.5	5.650	$8.74\cdot10^{-2}$	0.951	$1.64\cdot10^{-8}$	$5.31\cdot10^{-4}$	$3.30\cdot10^{-5}$	$2.20\cdot10^{-6}$	[5]
CEM I 52.5	5.800	$9.71\cdot10^{-2}$	0.476	$1.79\cdot10^{-8}$	$5.74\cdot10^{-4}$	$3.50\cdot10^{-5}$	$2.36\cdot10^{-5}$	
Cement industry (EPD)	2.451	$6.58\cdot10^{-2}$	0.691	$1.50\cdot10^{-8}$	$8.30\cdot10^{-4}$	$1.2\cdot10^{-4}$	$1.0\cdot10^{-4}$	[6]
Stone powders and aggregates								
Quartz powder 0-0.22 mm	0.820	$3.16\cdot10^{-2}$	$2.34\cdot10^{-2}$	$4.98\cdot10^{-9}$	$1.58\cdot10^{-4}$	$6.75\cdot10^{-6}$	$5.57\cdot10^{-6}$	[5]
Quartz sand	0.539	$1.29\cdot10^{-2}$	$1.02\cdot10^{-2}$	$2.10\cdot10^{-9}$	$7.54\cdot10^{-5}$	$3.00\cdot10^{-6}$	$2.58\cdot10^{-6}$	
Sand	0.022	$1.49\cdot10^{-3}$	$1.06\cdot10^{-3}$	$2.30\cdot10^{-10}$	$6.57\cdot10^{-6}$	$2.99\cdot10^{-7}$	$2.39\cdot10^{-7}$	
Gravel	0.022	$1.49\cdot10^{-3}$	$1.06\cdot10^{-3}$	$2.30\cdot10^{-10}$	$6.57\cdot10^{-6}$	$2.99\cdot10^{-7}$	$2.39\cdot10^{-7}$	
Admixtures								
Superplasticizer (PCE based)	27.95	1.20	0.944	$3.29\cdot10^{-8}$	$1.19\cdot10^{-2}$	$5.97\cdot10^{-3}$	$5.85\cdot10^{-4}$	[7]

As binders, two cements, the first being a CEM I 52.5 R according to [8] and the second being a micro-cement with strongly reduced particle size, were selected for the investigations. No product specific life cycle inventory data were available for the micro-cement, but as it 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 a slight increase in renewable primary energy consumption, assuming the separation process is powered by a renewable energy source. As the availability of supplementary cementitious binder materials may decline relative to future concrete demand, no supplementary cementitious materials were included in this research.

Coarse and fine aggregate fractions consisting of inert quartz gravel and sand fractions, inert quartz powders and a silica fume 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.

The particle size distribution of all granular constituents was optimized using the CIPM Model by Fennis [14] and adjusted to yield mixes with maximum packing density and minimum voids content. A detailed description of this procedure can be found in [3, 4]. The particle size distribution of the solid materials used is shown in Fig. 1. The silica fume is not included in herein, as agglomeration causes the measurement of an unrealistically coarse particle size distribution in densified product. Additionally, a superplasticizer was also included in the mixtures and dosed according to the recommendations made in [14].

Table 2. Properties of cements and inert aggregates investigated.

Reactive components				
Property	Dimension	CEM I 52.5 R	Micro-cement	Silica fume
Density [9]	[g/cm^3]	3.117	3.110	2,225
Blaine value [10]	[cm^2/g]	5800	6900	-
Time of initial set [11]	[min]	170$^{1)}$	77	-
Compressive strength $f_{c,28d}$ [12]	[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[9, 13]	[kg/dm^3]	2.648	2.650	2.650	2.61	2.51	2.54
Water absorbtion [13]	[m.-%]	-	-	0.2	0.3	1.8	1.5
Blaine value [10]	[cm^2/g]	18.000$^{1)}$	1448	-	-	-	-

1) Data supplied by producer

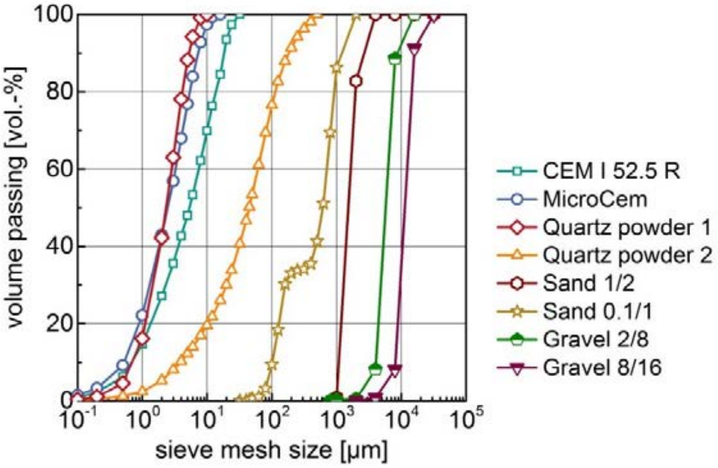

Fig. 1. Particle size distribution curves of the cements and inert granular constituent materials used

4. Composition and properties of investigated mixes

Based on the raw materials detailed in Sec. 3, a total of 6 different concrete mixes with cement contents ranging between 4 vol.-% and 10 vol.-% of all solid particles 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 to be decreasing from 10 vol.-% to 6, 5 and 4 vol.-% of the total solids volume contained in each mixture. Each mixture contained only one cement, either the CEM I 52.5 R or the micro-cement described in Sec. 3

Thirdly, the volume content of each inert granular material was adjusted to maximize the inert material content in the concrete while taking into consideration the influence of cement particles on the packing density. The particle packing model CIPM by Fennis [14] 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 [14].

The composition of the mixes detailed in Table 3 is characterized by cement contents between 113 kg/m^3 to 268 kg/m^3 in the fresh concrete of either the CEM I 52.5 R or the micro-cement. Additionally, in one mixture the cement

CEM I 52.5 R was combined with micro-silica fume by replacing 5 % by mass of the cement by the corresponding mass of micro-silica fume (referred to as SF-CEM I). Hereby the effect of an improved interfacial transition zone was studied. The reference concrete was adjusted to have a w/c-ratio of 0.43 with a cement content corresponding to the minimum requirements of EN 206-1 [15].

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
Grain size distribution (fit parameter n)	[-]	0.34	0.34	0.34	0.34	0.34	0.34
Cement type	[-]	CEM I	µCEM	SF-CEM I	CEM I	CEM I	CEM I
Mixture composition							
Cement	[kg/m³]	113	111	109	138	162	268
Quartz powder 1		96	96	96	94	92	91
Quartz powder 2		120	121	120	118	69	23
Sand 0.1/1 (mm)		519	520	520	490	497	441
Sand 1/2 (mm)		434	435	434	424	415	436
River gravel 2/8 (mm)		482	483	482	471	461	459
River gravel 8/16 (mm)		506	507	506	495	484	482
Water		87	85	87	106	126	130
Superplasticizer (PCE based)		6.5	6.4	6.5	6.0	5.7	6.2
w/c-ratio	[-]	0.64	0.64	0.65	0.67	0.69	0.43
Mixture properties							
Compressive strength $f_{cm,28d}$ [18]	[MPa]	76.9	79.0	76.6	69.8	58.2	102.6
Degree of compactability c [16]	[-]	1.25	1.21	1.19	-	-	-
Flow value a [17]	[mm]	-	-	-	390	450	480
Inverse carbon. resistance R_{ACC}^{-1} Mean value / standard deviation	[(10^{-11} m²/s)/ (kg/m³)]	18.91 / 6.83	0.39 / 0.33	14.74 / 5.63	29.59 / 9.69	42.91 / 12.95	--
Global warming potential (GWP)	[kg CO_2/m³]	75	74	76	87	97	146

The fresh concrete was tested for its compactability c according to [16] or its flow value a according to [17] depending on the flow characteristics of the mixture. Specimens were casted, 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, then tested for their compressive strength according to [18]. The corresponding results are detailed in Table 3 and show that the investigated concretes provide high compressive strengths combined with significantly reduced environmental impact compared to standard concretes. The environmental impact of each concrete is represented here by its global warming potential (GWP) and has been calculated based on the environmental impact and content of each raw material as specified in Sec. 3.

Besides the properties in the fresh state and the mechanical properties, the concretes were also tested for their durability under common environmental exposures such as freeze-thaw attack with de-icing salt and carbonation. These experimental results served in the calculation of the service life expected for these concretes.

Fig. 2 shows the results of freeze-thaw tests conducted according to the CDF-method as described in [19] and [20].

As can be seen from the results detailed in Fig. 2, neither the tested reference concrete with a cement content of 10 vol.-% corresponding to 268 kg/m³, 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 [15] with a maximum allowable spalling of 1500 g/m². This result was expected. However, the experimental data also shows 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.-%, respectively. 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 than the reference concrete with a cement content of 10 vol.-% and a w/c-ratio of 0.43.

This result in combination with the declining performance of mixes with increasing cement content 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. 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.

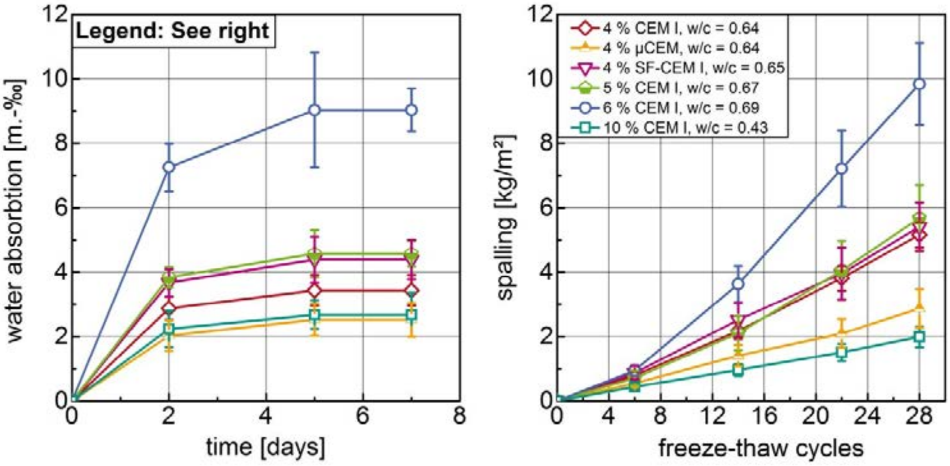

Fig. 2. Measured capillary suction (left) and concrete spalling (right) of investigated mixes in the CDF-test according to [19] and [20].

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 fume. It was dosed to the coarse aggregates in order to enhance a localization of these particles on the coarse aggregate surfaces. The comparison of this mix with the corresponding reference mixture, i.e. the mix containing 4 vol.-% of Portland cement, does not show any difference in the free-thaw-behavior. Here it appears that 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 fume exhibits higher water absorption than the mix without silica.

A very important aspect in the evaluation of the durability of the investigated concretes is their resistance against a CO_2-induced carbonation. Therefore, beam shaped samples with dimensions of 100 x 100 x 440 mm³ were casted, demoulded after 2 days and stored in 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 CO_2 concentration of 2 vol.-% at 20 °C and approximately 70 % r. h. Both the samples carbonating under normal and under increased CO_2 concentration were investigated for their carbonation depth by splitting the samples at four points along the length of the beam and applying phenolphthalein to the surfaces of the split cross sections. The carbonation depth of each concrete was determined using one beam, measuring inward at 3 points along each of the 4 edges of the split surfaces. The mean value of the carbonation depth was formed for each mixture out of the 48 measurements taken from the corresponding beam.

As can be seen from Fig. 3 (left), the reference concrete (w/c = 0.43) subjected to normal carbonation (i.e. approximately 0.04 vol.-% of CO_2) does not show any carbonation at all, whereas the samples with reduced cement content exhibit a significantly increased carbonation. The worst performance in this comparison was also observed 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 fume and the corresponding mix without 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 CO_2 in

Fig. 3 (right). In this test setup the reference 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. Independently of the test set-up, the carbonation depth was lower than 1 mm, showing a good carbonation resistance, albeit a diminished carbonation resistance when compared to the reference mixture.

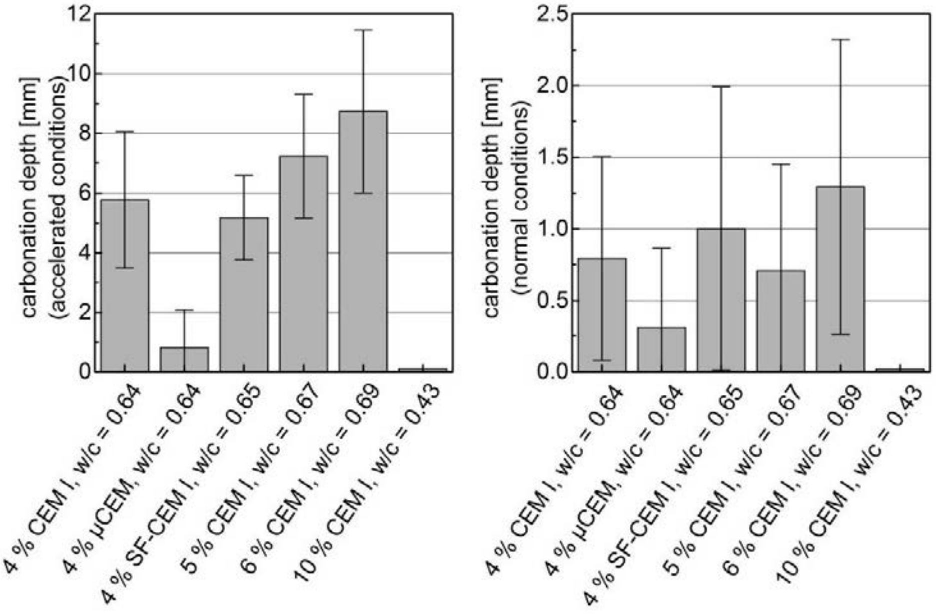

Fig. 3. Carbonation depth of concretes exposed to natural CO_2 environment at 20 °C and 65 % r. h. (left) and 2 vol.-% of CO_2 at 20 °C and approximately 70 % r. h. (right) at an age of 56 d (test procedure see text)

5. Service life design as a key to sustainable buildings and structures

As illustrated by Eq. 1, maximizing the 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 single sided focus on a pure reduction of environmental impact while neglecting the durability and thus the sustainability of the designed structures.

The service life design process is dominated by assessing the alteration – i.e. ageing and often deterioration – of the material on one hand and the varying environmental exposures on the other. This requires in-depth knowledge of the deterioration mechanisms of concrete and on the variance of the influencing factors over time. The procedure of service life prediction will, in the following, be illustrated by means of the carbonation process applied to green concretes as presented in Sec. 4.

The time dependent carbonation of concrete can be described using Eq. 2, in which xc(t) describes the carbonation depth in (mm) at the time t. The dimensionless parameters ke, kc and kt take into account environmental conditions, curing and testing effects. RACC-1 is the inverse effective carbonation resistance of concrete and εt is the corresponding error term in ((mm^2/years)/(kg/m^3)). CS describes the surrounding CO_2-concentration in (kg/m^3) and W(t) is the dimensionless weather function, see [21]. With the experimental data depicted in Fig. 3, RACC-1 can be calculated for the green concretes (see Table 3).

$$x_c(t) = \sqrt{2 \cdot k_e \cdot k_c \cdot \left(k_t \cdot R_{ACC,0}^{-1} + \varepsilon_t\right) \cdot C_S} \cdot \sqrt{t} \cdot W(t) \qquad (2)$$

As a limit state criterion xc(t) = c, with c being the concrete cover, is introduced. The failure probability pf is defined as the probability for exceeding this limit state within a defined reference time period.

The loss of durability, i.e. the increase of the deterioration with time, reduces the reliability of a structure. In order to be able to evaluate this reliability at any age of the structure, a reference period for the service life has to be specified [22]. Based on Eq. 2, the time at which depassivation of the reinforcement occurs can be determined. By introduction of the reliability index β, a direct correlation between β and the failure probability pf is obtained. In case of a normally distributed limit state function Z = R – S (R: Resistance, S: Action), the failure probability pf can be directly determined using Eq. 3.

$$p_f = p\{Z<0\} = \Phi(-\beta) \tag{3}$$

The variable Φ(-β) denotes the distribution function of the standardized normal distribution (see [23]). The correlation between various values for the failure probability pf and the reliability index β is shown in Table 4. Note e.g. that the often used 5 % quantile in civil engineering is equal to a failure probability of 5·10-2, which corresponds to a reliability index β = 1.645.

Table 4. Values for the failure probability pf and the related reliability index β [23].

p_f	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
β	1.28	2.32	3.09	3.72	4.27	4.75	5.20

The target values of the reliability index, βtarget, depend on the consequences of failure (loss of serviceability) and the relative cost of safety measures. Table 5 contains target values of the reliability index β for building components in the serviceability limit state (SLS), see [24, 25]. Considering the case of depassivation of the reinforcement due to carbonation or chloride ingress, the target reliability index is recommended as β = 1.3 according to [21].

Table 5. Target values of the reliability index β depending on the relative cost of safety measures.

Relative cost of safety measures	Reliability index β [24]	Reliability index β [25]
High	1.3 (pf ≈ 10 %)	1.0 (pf ≈ 16 %)
Moderate	1.7 (pf ≈ 5 %)	1.5 (pf ≈ 7 %)
Low	2.3 (pf ≈ 1 %)	2.0 (pf ≈ 2 %)

Fig. 4 shows a comparison of the resulting service life prediction for concrete structures subjected to carbonation with 40 mm mean concrete cover thickness (8 mm standard deviation) using a green concrete containing 113 kg/m³ (see Fig. 3, 4% CEM I, w/c-ratio = 0.64) and a reference concrete containing 320 kg/m³ of a CEM I 42.5 R with a w/c = 0.60 as described in [26, 27]. Further parameters in Eq. 2 were set according to the example in [27], representing environmental exposure conditions in the city of Munich, Germany. The reference concrete reaches the target reliability index of βtarget = 1.5 chosen in this case after 100 years, the selected green concrete after 72 years.

Combining the measured performance of the green concretes with the durability parameters determined by experiment and the probabilistic service life prediction, it is now possible to evaluate the sustainability potential as described in Eq. 1. Table 6 contains the results for the BMSP of a green concrete as compared to a normal concrete evaluated for a moderate reliability index of 1.5 (see Table 5) in the case of CO_2-induced carbonation described above. Although the predicted service life of the green concrete is thirty years shorter than that predicted for the normal concrete, its high performance and reduced environmental impact compensate for this deficit within the sustainability potential index.

It has to be stated that the obtained result is just one among other examples, as only strength and carbonation are considered for the parameters of performance and service life in Eq. 1. Different results would be obtained if e.g. the freeze-thaw characteristics or the chloride ingress is taken into consideration. Moreover, combinations of these effecting parameters might be considered. However, further research is necessary to develop a suitable extended approach. Nevertheless, the simplification included so far does not put into question the particular value of Eq. 1 in view sustainability considerations.

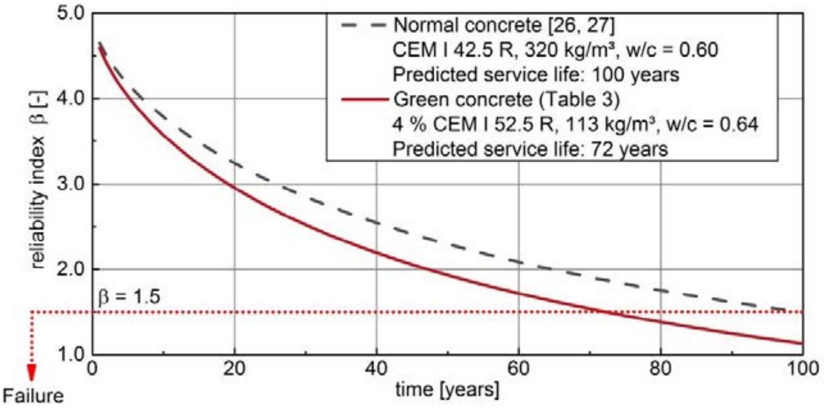

Fig. 4. Comparison of exemplary service life predictions between a developed green concrete and a normal concrete taken from literature data [26, 27].

Table 6. Evaluation of the sustainability potential of a green concrete in comparison to a standard concrete.

Concrete type	Dimension	Normal concrete	Green concrete 4 % CEM I 52.5 R
Cement type	-	CEM I 42.5 R	CEM I 52.5 R
Cement content	kg/m³	320	113
Water to binder ratio	-	0.60	0.64
Inverse carbonation resistance R_{acc}^{-1} (mean value / standard deviation)	$(10^{-11}$ m²/s)/(kg/m³)	13.4 / 5.2	18.9 / 5.6
Calculated service life	years	100	72
Compressive strength	MPa	38.4	76.8
Environmental impact	kg CO_2/m³	214	76
BMSP (See Eq. 1)	MPa·years/(kg CO_2/m³)	17.9	72.8

6. Structural performance of graded concrete members

In order to investigate the load bearing characteristics of different types of concrete, deflection controlled three-point-bending tests, based on the DAfStb-Guidelines for fiber reinforced concrete [28], were carried out. In the experiments, steel reinforced and unreinforced beams with homogenous as well as with vertically graded concrete distributions over the cross section were tested. The graded beams typically contained a layer of UHPC in the tension zone and cement-reduced concrete in the compression zone, the transition zone being graded with layers of blends of these two root mixtures.

The beams with a cross section of 150x150 mm², 525 mm in length and, in the case of reinforcement, three equally spaced 8 mm steel reinforcing bars with 15 mm of concrete cover, were rested upon abutments separated by 450 mm and loaded centrally. The loading occurred in three stages with an increasing deflection rate. In the first stage, the deflection was increased at a rate of 0.1 mm/min until 0.5625 mm deflection was reached, corresponding to 0.125 % of the distance between the abutments. The stage was followed by a short pause, during which the beams were investigated for cracks and the crack widths were measured. In the second stage, the deflection was increased by 0.3 mm/min until the deflection of 2.625 mm was reached, corresponding to 0.50 % of the beam length. Again, cracks were marked and crack widths measured in the ensuing pause. In the third stage, the deflection rate was increased to 1.0 mm/min. The resulting load was continually recorded and the experiments were terminated when the load had decreased to 10 % of its maximum in the case of unreinforced beams, or the total deflection of 5 mm was reached in reinforced beams. Approximately 45 minutes were required for the testing of a single beam from mounting to demounting. Fig. 5 shows resulting loading versus deflection curves for reinforced beams together with an estimate of the binder material contained therein.

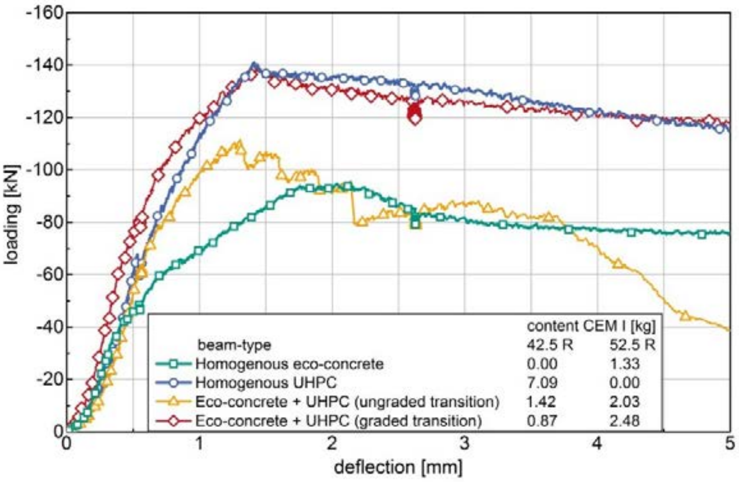

Fig. 5. Loading versus deflection curves of steel reinforced homogenous and graded beams. The cement content of each beam corresponds to unreinforced cross-sections.

It can be seen in Fig. 5 that at small deflection, the beams show quite similar behavior with the exception of the combination between eco-concrete and UHPC with a graded transition zone, which exhibits the highest load at all corresponding deflections. As the deflection increases beyond 0.5 mm, the homogenous eco-concrete beam shows the weakest load bearing capacity. The combination of eco-concrete and UHPC without a graded transition zone improves the performance of the beam somewhat, especially below 2 mm total deflection, but it is surpassed by the homogenous UHPC-beam and the beam with a graded transition zone. The UHPC-beam and the beam with a graded transition zone perform best and behave nearly identically above 1.5 mm deflection. These results are particularly interesting, when considering the amount of binder contained in each beam, which is a good indicator for their corresponding global warming potential. The results suggest that by strategically grading the concrete distribution over the cross section in bending members, load bearing characteristics of homogenous UHPC-beams can be achieved and even surpassed while using only a fraction of the binder material. In this case, the reduction of binder material between the homogenous UHPC-beam and the beam with a graded transition zone is approximately 50 %. The results shown here, however, are preliminary in nature. Further investigations are required and are currently ongoing.

7. Summary and conclusions

It is insufficient to consider only the environmental impact of the constituent concrete materials when evaluating the sustainability of concrete. Two further relevant parameters, the mechanical performance and the durability (service life) of the concrete, have to be taken into account as well. By means of the introduction of the Building Material Sustainability Potential (BMSP) index, these three interdependent parameters may be considered concurrently in order to optimize the sustainability.

It has been demonstrated that cement-reduced concrete can be produced while maintaining or even improving performance in compressive strength, raising potential for discussion of 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 one such concrete compared to a standard concrete indicates potential for a significant sustainability benefit when choosing the green 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 indeed expires.

Bending tests on reinforced graded concrete beams, where eco-concrete was placed in the compression zone and UHPC in the tension zone revealed a very positive load-deflection behaviour, while the environmental impact could be keep rather low compared to other concretes beams. However, further investigations are necessary to take full profit of the positive structural performance of graded concrete members when eco-concrete is applied.

The cement-reduced concrete mixtures presented are a first step toward producing sustainable concrete and abstaining from supplementary cementitious materials. While the BMSP of the examined green concrete greatly exceeds that of the reference concrete presented, more research regarding the durability of these mixtures must be performed.

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