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Design approaches for sustainable concrete mixes and structural components

Alternativas de diseño para mezclas de hormigon sustentable y componentes estructurales

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Abstract

Changes in the current use of concrete materials and design approaches are mandatory in order to comply with the requirements imposed on future sustainable concrete structures. Before this background, the article indicates the design of sustainable concrete mixes (green concretes or eco-concretes) and the structural components made from them. Such concretes are characterized by a pronouncedly reduced CO_2 footprint compared to conventional structural concretes made purely with Ordinary Portland Cement (OPC).

After an introduction to the sustainability problems of today's structural concretes, the basic approaches for the development of sustainable concrete are presented. The specific parameter Concrete Sustainability Potential is introduced, which combines the main effecting parameters such as environmental impact, service life (durability) and performance (strength). An overview of possibilities available today for producing sustainable concrete mixtures is given. For good reasons, emphasis is placed on such sustainable concretes, in which a large proportion of the OPC is replaced by rock powders.

Finally, a new and innovative relationship for sustainability design is introduced. This concept is equally applicable to concrete as a material and to components made from it. The article concludes with considerations on the implementation of this new concept in practice.

Keywords: Sustainable concrete, concrete composition, cement replacement, sustainability.

Resumen

Cambios en los materiales utilizados actualmente para el hormigón y en los enfoques de diseño son requisitos obligatorios impuestos a las futuras estructuras de hormigón sostenible. En este sentido, este artículo aborda el diseño de mezclas de hormigón sustentable (hormigones verdes o eco hormigones) y los componentes estructurales elaborados a partir de ellas. Estos hormigones se caracterizan por una huella de CO_2 notablemente reducida en comparación con los hormigones estructurales convencionales elaborados exclusivamente con cemento Portland ordinario (OPC).

Tras una introducción a los problemas de sostenibilidad de los hormigones estructurales actuales, se presentan los enfoques básicos para el desarrollo de hormigones sostenibles. Se introduce el parámetro específico Potencial de Sostenibilidad del Concreto, que combina los principales parámetros que lo afectan, como el impacto ambiental, la vida útil (durabilidad) y el rendimiento (resistencia). Se ofrece una visión general de las posibilidades disponibles hoy en día para producir mezclas de hormigón sostenibles. No en vano se pone especial énfasis en estos hormigones sostenibles, en los que una gran parte del OPC se sustituye por polvo de roca.

Finalmente, se introduce una relación nueva e innovadora para el diseño sustentable. Este concepto es igualmente aplicable al hormigón como material y a los componentes fabricados a partir de él. El artículo concluye con consideraciones sobre la implementación de este nuevo concepto en la práctica.

Keywords: Hormigón sustentable; composición del hormigón; reemplazo de cemento; sostenibilidad.

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1. Introduction and overview

Today it is well known that the production of concrete is associated with high CO_2 emissions which result mainly from cement manufacturing. However, it was not until the turn of the millennium when that awareness was raised that the production of cement is one of the most energy-intensive and CO_2-intensive industries in the world, surpassed today only by energy production through the burning of fossil fuels, the traffic and the steel production. It is estimated that the cement industry is currently responsible for about 7-8 % of the global man-made CO_2 emissions.

These emissions have to be significantly reduced, as a contribution of the concrete industry, so that the international agreement to limit global warming to a maximum of 1.5 degrees Celsius above pre-industrial level can be reached. This target was set in the Paris Agreement of 2015 to prevent the worst effects of climate change. It is therefore not surprising that many strategies have been developed, particularly in the past decade, to significantly reduce the CO_2 footprint associated with concrete construction.

When thinking of a solution to this sustainability problem, three basic ideas can be identified. The first and very simple solution could be to strive for a tremendous reduction of the use of concrete, e.g. by shifting away from concrete to other building materials such as timber. However, in many cases this is impossible, as for many applications, no alternatives to concrete are available. Further, worldwide economic success is very much linked to an efficient infrastructure, thus relying on concrete. As a consequence, concrete became by far the most important building material of the modern industrial age. Its decisive advantages - comparatively high strength and durability associated with high availability in huge quantities and cost-effective production anywhere in the world - are up to nowadays not even remotely matched by any other building material. Concrete has made possible the economic development of the industrial nations over the last 100 years. With an annual production volume of currently approx. 8 billion m³ of concrete, economic development worldwide would not be possible without it.

The second solution consisting of completely replacing cement with another binding agent cannot be implemented either. To date, there is no alternative binder that could even come close to the positive properties of Portland cement clinker. And, if one considers the huge quantities of suitable base materials for binder production that have to be available, all over the world, this solution is also ruled out from the outset.

The third solution consists of retaining conventional cement production but capturing the CO_2 emissions. The technology of capturing CO_2 has made significant progress in the last years, and currently, pioneering pilot projects are testing the scalability of the technique. If this technology proves successful, it will probably last decades before every cement plant in the world has been converted accordingly. Even more important is the fact, that carbon capture and storage technology (CCS) requires adequate storing facilities. Here progress unfortunately is often hindered by public acceptance problems. Further, it must also be accepted that the price of cement will rise significantly.

In view of the three alternatives for avoiding CO_2 emissions in concrete production described above, which cannot be implemented for various reasons, the only remaining option for the coming years is to reduce CO_2 emissions by making suitable changes to the composition of cement and concrete.

Two different or complementary strategies, respectively, can be established along the service life of a concrete structure. They aim (i) to reduce CO_2 emissions during the construction phase including concrete production, and (ii) to maximise CO_2 absorption during the operation phase. Both targets can be achieved by an appropriate adaption of the composition of the concrete and by additional measures during production, placing and curing.

(Figure 1) illustrates the development of CO_2 emission and CO_2 absorption over time as they are today and as they should be in the future. With the help of suitable developments, the overall CO_2 balance tends towards zero and can ideally even become negative in the future after a long service life of a concrete structure. In order to drive forward corresponding developments, the German Research Foundation has been funding the Priority Programme SPP 2436 entitled Net-Zero Concrete since summer 2024 (Deutsche Forschungsgemeinschaft DFG, 2024).

The article at hand focuses on the possibilities of reducing CO_2 emissions in the construction phase by optimising the composition of the concrete. This can be achieved by various strategies, which are discussed in this article.

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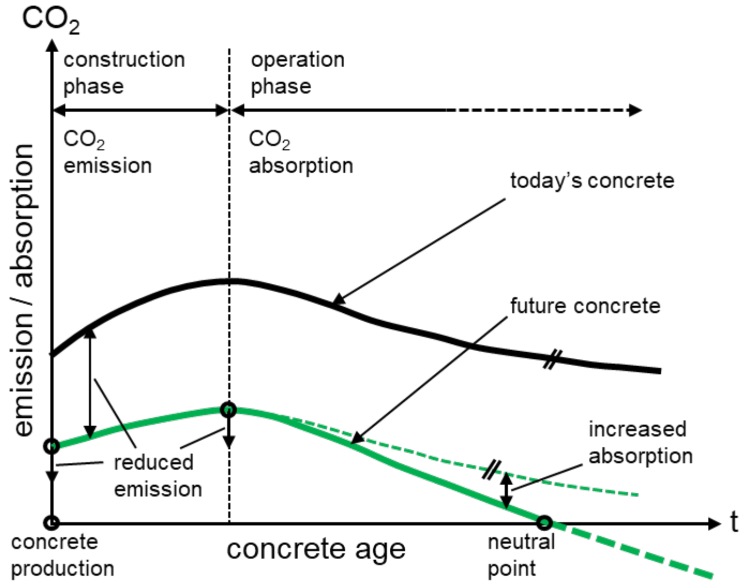

Figure 1. CO_2 emission and absorption over the life cycle of a concrete structure for today's concrete and for future concrete

For comparative and evaluative considerations, the introduction of the Concrete Sustainability Potential is an important tool as it combines the governing parameters of environmental impact, service life (durability) and performance (strength). Further, an overview of the possibilities available today for producing sustainable concrete mixtures having an improved CO_2 footprint is given. Hereby, emphasis is placed on such eco-concretes for which a large proportion of the cement is replaced by rock powders.

Finally, a new and innovative relationship for sustainability design is introduced. This concept is equally applicable to concrete as a material and to structural components made from it.

2. The sustainability potential

From the facts indicated in the previous chapter, it becomes evident that at first sight the concrete composition must be fundamentally changed. In particular, the content of Portland cement clinker, which is inflicted with very high CO_2 emissions, must be reduced or must be substituted as far as possible by more environmentally friendly binders.

However, when evaluating the sustainability of concrete, singularly addressing the CO_2 emissions falls short. For example, if one single high CO_2 emission is associated with the production of high-quality concrete that may withstand all critical exposures for many decades without repair or replacement, then the initial adverse emission has to be evaluated differently. This means that high performance and durability are required from the building material itself in the case of structures, which, however, cannot be guaranteed in principle by ecologically optimized concrete. Therefore, the parameters of performance and service life must be considered equally with the environmental impact in a balance sheet related to sustainability. Taking these considerations into account, the Concrete Sustainability Potential (CSP) was introduced as defined by (Equation 1), see (Müller et al, 2016); (fib Model Code, 2023):

$$\textbf{concrete sustainability potential (CSP)} = \frac{\textbf{service life } (t_{SL}) \cdot \textbf{performance } (f_{ck})}{\textbf{environmental impact (GWP)}} \qquad (1)$$

Herein, f_{ck} is the characteristic strength of the concrete in [MPa] representing the possible performance of the material, t_{SL} is the potential service life of the concrete under the specific environmental actions to be expected in the lifetime of the building member in years [a], and GWP is the environmental impact associated with the production of the concrete including all raw materials expressed by the lead parameter Global Warming Potential (GWP) in eq. kg CO_2; for further details see (fib Model Code, 2023).

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(Equation 1) represents a simple tool to quantify the advantages and disadvantages of a specific concrete type regarding 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 should be noted that (Equation 1) may also be applied to structural components.

According to (Equation 1), three basic approaches to 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-mentioned approaches appears reasonable.

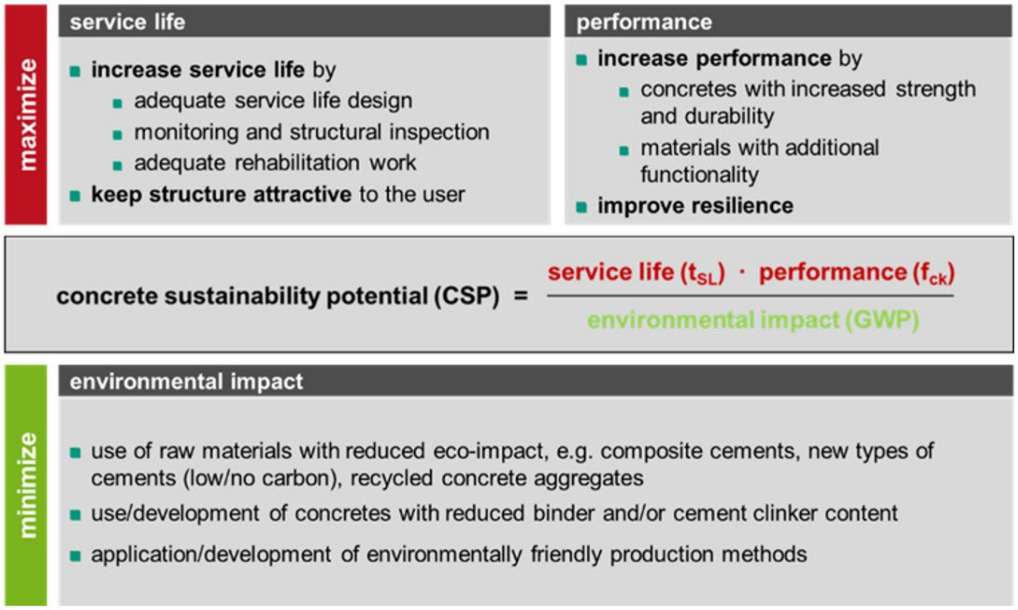

Figure 2. Overview of approaches and tools to develop sustainable concretes

(Figure 2) provides an overview of various methods for maximizing the service life and the performance of concrete and concrete structures and for minimizing environmental influences and thus improving sustainability:

- In terms of service life, structural monitoring and structural inspection as well as applying sustainable repair work are particularly suitable methods for increasing the service life of a structure. In this way, the building also retains its attractiveness for the user. The service life assessment at the stage of design is also of great importance. If a structure is only used for a short period, for example in industrial construction, significantly lower quality of concrete is acceptable than for structures which are used over long periods, as is the case with structures of great economic importance (tunnels, bridges, dams). Note that currently the higher the quality of concrete the higher the associated CO_2 emissions.
- In terms of concrete performance, higher strength results in lower material consumption for the same load-bearing capacity of components. Further, an increase in durability is advantageous because the service life of the structure is extended and early repair is avoided. Improved overall resilience also leads to lower CO_2 emissions when using concrete.
- There are essentially three different ways to reduce the environmental impact by reducing CO_2 emissions. Firstly, concrete raw materials should be used that have a lower CO_2 footprint from the outset. It is also beneficial to use recycled concrete as aggregate. Furthermore, efforts must be made to use as little Portland cement clinker as possible. Finally, the overall CO_2 emissions can also be reduced by optimizing the production of concrete and its transport.

Related to the environmental impact, i.e. the use of raw materials with reduced eco-impact, e.g. composite cement, new types of cement (low/no carbon footprint), recycled concrete aggregates and the use/development of concretes with reduced binder and/or cement clinker content, chapter 3 of this paper indicates further details.

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As the use of Portland cement is indispensable for producing structural concrete today, the question arises as to what the most efficient way is when this binder is applied in view of minimizing the environmental impact. In this context, a concrete data evaluation by Damineli (Damineli et al, 2010) is very revealing. They have defined a so-called binder intensity, and have plotted this binder intensity over the compressive strength (see Figure 3).

The decreasing binder intensity with increasing compressive strength, as may be depicted in (Figure 3), indicates that the use of Portland cement is more efficient (sustainable), the higher the strength is. This is more pronounced as for higher strength concrete the cross-section of members may be reduced, i.e. a reduction in mass consumption is achieved at a given load-bearing capacity.

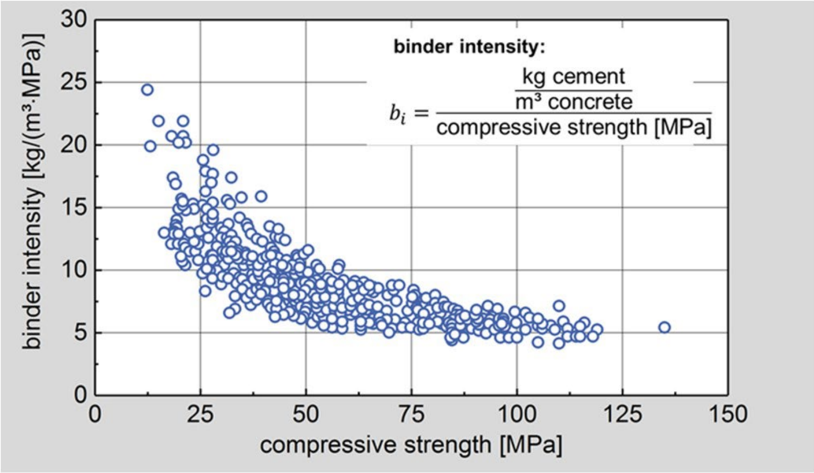

Figure 3. Efficiency of the used amount of binder in typical structural concretes depending on the strength of concrete (Damineli et al, 2010)

(Figure 3) also indicates that for normal and low-strength concrete the amount of cement used for these concretes is not necessary for the reason of strength, however, it is beneficial for workability and durability reasons. This means that a large amount of cement may be saved if workability and durability are guaranteed by other measures. This would be very efficient in view of sustainability as roughly 90 % of all concretes used in practice have a compressive strength between 20 and 50 MPa.

From (Figure 3) the general conclusion may be drawn that either the reduction of the binder content of ordinary strength concrete or the use of high strength concrete lead to a sustainable use of concrete. The concept of reducing the binder content for ordinary structural concrete while keeping its advantageous technical properties is further analysed in the subsequent chapter 3 of this paper.

3. Sustainable concrete mixes

3.1 Approaches

In order to meet the requirements of sustainability concerning concrete as a building material, the currently used concrete compositions must be fundamentally changed. In particular, the Portland cement clinker (PC), which is associated with extremely high CO_2 emissions, must be substituted as far as possible by more environmentally friendly binders, for example, secondary cementitious materials (SCM) and/or new types of hydraulic binders. Further, substitution with inert fines of aggregates is also a very promising approach to significantly reduce the carbon footprint of concrete mixes.

(Figure 4) summarizes the different strategies for clinker replacement by subdividing these strategies into four different kinds of approaches. The composition of ordinary structural concrete in volume parts is indicated by the first column (left). Apart from the aggregates which comprise a volume of approx. 70 %, the remaining 30 vol % are filled by water, cement (or substitute products), additives and admixtures.

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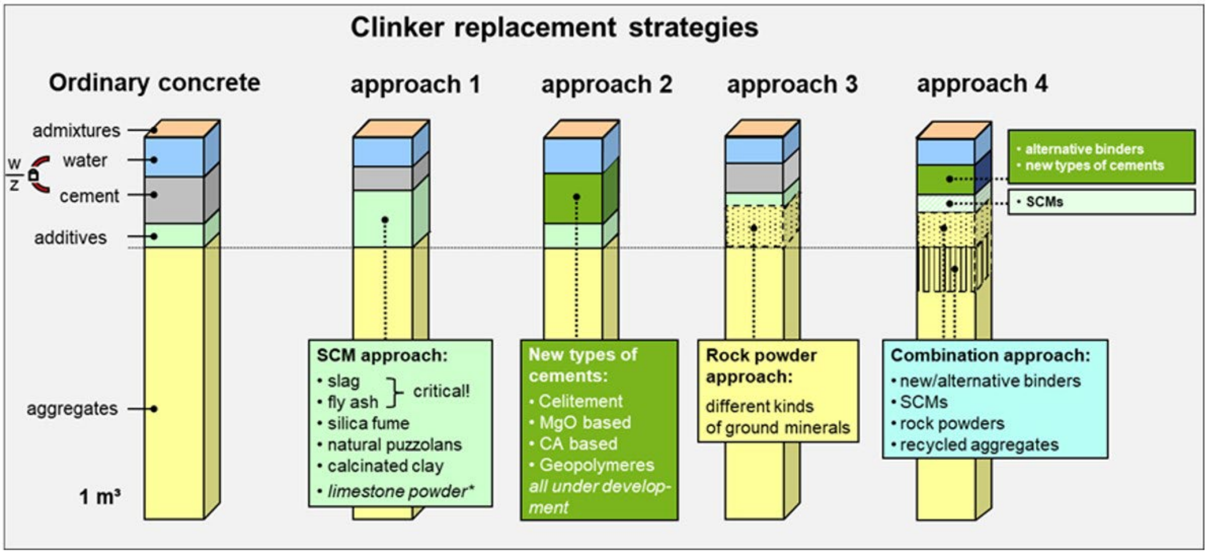

Figure 4. Strategies and examples for the reduction or replacement of Portland cement clinker for the production of structural concrete

Approach 1 (see (Figure 4)) shows a pronounced replacement of the cement by SCM additives. The materials blast furnace slag (BFS) and fly ash (FA) – being often used today – must be viewed critically. BFS is a by-product of steel production. Therefore, its availability is limited and BFS may be unlikely to replace PC completely due to the huge amount of PC which is needed worldwide. FA is a waste product resulting from coal combustion. However, the energy generation from coal combustion is extremely problematic due to the high associated CO_2 emissions. Therefore, this type of energy is coming to an end in a continuously increasing number of countries. This means that FA will become more and more scarce in the concrete industry and will no longer be available at some point in time. Silica fume (SF) is also a by-product having a very limited availability in the market. The other SCM mentioned in (Figure 4) (approach 1) can be expected to increasingly enter the market. However, there is still a considerable need for research in the area of calcinated clays.

Approach 2 (see (Figure 4)) assumes that Portland cement clinker will be completely replaced by new types of cement/binder. In addition to the product Celitement (Stemmermann et al, 2020) these are primarily MgO- and CA (= CaAl)-based binders as well as geopolymers. Intensive research is currently being carried out related to these binders. Despite some successes and promising approaches, however, it must also be noted that no binder has yet been developed or is under development which, in terms of its technical properties, is equivalent to the product Portland cement clinker.

Approach 3 (see (Figure 4)) is characterized by the fact that a large proportion of the cement is replaced by finely ground inert aggregates. The underlying idea is that these aggregates form the necessary fines in the concrete mix to ensure the cohesion and the processing of a concrete mix, and also contribute to the concrete strength, which is, however, mainly provided by the remaining Portland cement clinker. This approach, which dispenses completely with the use of SCM, is further described below.

Approach 4 indicated in (Figure 4) is a combination of approaches 1 to 3 with the additional use of recycled aggregates for concrete production. The amount of recycled aggregates may cover a large part of the total aggregates.

An alternative to these four approaches is the CO_2 avoidance strategy by carbon capture and storage (CCS) or carbon capture and use (CCU) concepts being under development in some countries. These concepts allow the conventional production of PC as the associated CO_2 emissions are captured by applying available technologies. Although this is a promising approach, it must be noted that there are numerous technical, economic and social problems associated with it. It is very unlikely that a sufficiently large volume of PC may be produced by applying these technologies, in particular not until 2045, when the zero CO_2 emission target should be reached in Europe.

Approach 1 is mainly used by the cement industry to significantly reduce the mass proportion of Portland cement clinker in the binder for concrete. As a result, there is a very wide range of more environmentally friendly, standardized binders/cements for concrete on the market today. Approaches 2 and 3 are the focus of the current research. This research is entering new areas that are not the case with the cement

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industry approaches, as it has to stay within the framework of established regulations and codes with its modified binders to be able to serve the needs of the market.

3.2 Rock powder approach

As already mentioned above, approach 3 was scientifically investigated in more detail by (Müller et al, 2016) (Müller et al., 2019). One of the main reasons for this was the positive result of preliminary investigations, which showed that it is possible in principle to reduce the cement content of concrete from over 300 kg/m³ to values of around 100 kg/m³ if the missing cement quantity is replaced by aggregate powders without losing any of the concrete's essential properties. A further positive aspect is that rock powders are available for the time being or may be easily produced in large amounts anywhere in the world.

However, this change in the composition of concrete, i.e. the replacement of cement with rock powders is associated with considerable complications. Elaborated particle packing density model approaches must be used to determine the composition of the fines properly. To ensure sufficient workability – the water content of the concrete must be drastically reduced to prevent the water-cement ratio from increasing too much when the cement content reduces – extensive preliminary tests with various superplasticizers proved necessary. Note that superplasticisers have been chemically designed to work with cement particles and not with fine aggregate particles which have different molecular surface properties.

(Figure 5) summarizes the important results of the extensive investigations given by (Müller et al, 2019). It shows the composition (left) of a standard structural concrete ("ord") and a green concrete ("green") produced according to approach 3. The right part of (Figure 5) shows the concrete properties determined in each case. While the strength parameters and the stiffness of the green concrete are even better compared to ordinary concrete, the lower resistance to carbonation and the insufficient frost resistance in particular are deficits. However, it appears that these disadvantages can also be compensated to a large extent by further developments. On the other hand, such green concrete could already be used wherever no frost attack is given. Its GWP is reduced to a value of approx. 50 % compared to that of ordinary concrete (here GWP considers all materials and processes).

Concrete composition

component		ord	green
type of cement	-	42,5 R	52,5 R
cement	[kg/m³]	320	113
water		192	87
paste content	[Vol.-%]	29	13
w/c ratio (eff.)	[-]	0,60	0,64
quartz powder 1	[kg/m³]	-	96
quartz powder 2		-	120
sand 0/2		550	955[1)]
gravel 2/8		635	480
gravel 8/16		640	505
plasticizer		-	6,5

1) splitted in two fractions 0.1/1 and 1/2 mm

Concrete properties

parameter		ord	green
compr. strength f_{cm}	[N/mm²]	38,4	76,9
modulus of elast. E_c		33700*	38030
spl. tensile str. $f_{ctm,sp}$		2,9*	2,3
flex. strength $f_{ctm,fl}$		4,4*	4,9
inverse carbonation resistance R_{ACC}^{-1}	[(10^{-11} m²/s)/kg/m³]	13,4	18,9
chloride migration coefficient $D_{RCM,0}$	[10^{-11} m²/s]	2,5	2,0
CDF frost spalling	[g/m²]	< 1500	2760
Global Warming Potential	[equ.kg CO_2/m³]	285	135

* according to *fib* Model Code 2010

Figure 5. Comparison of ordinary concrete C30/37 ("ord") and green concrete ("green", cement replacement by rock powder); concrete compositions (left) and concrete properties (right)

A rather particular aspect has to be considered when comparing the composition and the properties of conventional and green concrete produced by the rock powder approach. While the water-cement ratio increases from 0.60 to 0.64, the compressive strength increases from 38.4 to 76.9 MPa as well (see (Figure 5)). This is in contrast to Abram's well-established law, which states that with increasing water-cement ratio the compressive strength is decreasing. This means that green rock powder-type concretes behave differently than normal concretes, and that well-established relations for normal concretes are not necessarily valid for these types of green concrete.

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3.3 Problems associated with sustainable concretes

The positive development of hydraulic binders for concrete with regard to environmental issues due to the increasing substitution of Portland cement clinker is accompanied by a certain disadvantage resulting from the novelty or the lack of experience with these products, respectively. Thus, for classical concrete, whose binder consists essentially of Portland cement clinker and/or granulated blast furnace slag, a very large number of scientific studies are available with regard to a wide variety of material properties, as well as extensive long-term observations and practical experience. These findings have been reflected in material models and design approaches available to the design engineer. Since this is not the case for concretes with new binders, the necessary performance tests to ensure safety and durability are of great importance when building with these new types of concretes.

4. Structural design for sustainability

The Concrete Sustainability Potential as defined by (Equation 1) is a useful tool for making comparative considerations when selecting or specifying a concrete in advance of a construction project. This tool makes it possible to identify a specific concrete with a high sustainability potential that also meets the required technical specifications. However, in order to be able to carry out an engineering design of concrete for sustainability, (Equation 1) must be reformulated for various reasons. This also applies to the case that (Equation 1) is used for the design of components, which is possible in principle as well.

In design, target values have to be related to an upper or a lower limit. Hence, the inverse of the Concrete Sustainability Potential shall be considered. Further, it is very difficult to give limiting values for a property like sustainability, as it is not based on a defined physical dimension like strength or stresses. Hence, relative values should be determined, i.e. a calculated current value (“eco”) has to be divided by a reference value (“ref”) so that as a consequence the dimensions are cancelled.

Further, as the concrete strength is the basis for the design of a member, and is calculated from the requirements regarding the load-bearing capacity, it is kept constant both for “eco” and “ref” and thus cancelled in the design equation for sustainability, see (Equation 2).

Taking the aforementioned considerations into account, the general format for verification of concrete environmental performance is proposed with (Equation 2), which defines a limit state, see (fib Model Code, 2023):

$$ELS_{cal} = \frac{\left[\dfrac{\Sigma EI}{SL}\right]_{eco}}{\left[\dfrac{\Sigma EI}{SL}\right]_{ref}} \leq ELS_{predefined} \leq 1.0 \tag{2}$$

ELS_{cal} is the calculated concrete environmental performance limit state, $ELS_{predefined}$ is the limit value that defines the ELS criteria, EI is the environmental impact of concrete and concrete production and SL is the service lifetime.

The index ref indicates the value calculated for a reference concrete. The index eco indicates the value calculated for a concrete for which an optimization has been carried out in such a way that the predefined limit state criterion ($ELS_{predefined}$) is fulfilled.

For practical application, (Equation 2) can also be simplified, for example by focusing the limit state consideration exclusively on the CO_2-eq emission. In such case, ΣEI = CO_2-eq mass per cubic metre [kg/m^3] of concrete and SL = 1.0. For more details, see (Haist et al, 2022a); (Haist et al, 2022b); (fib Bulletin NN, 2024).

(Figure 6) shows an example of dimensioning according to (Equation 2). First, different concretes must be compared with each other in terms of their sustainability potential given on the y-axis, see (Figure 6), diagram top left. As a result, a specific ecologically optimized concrete can be selected. A further step is to optimize the structural component in terms of maximizing the load-bearing capacity while minimizing the concrete

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consumption (see (Figure 6), diagram top right). Both considerations and optimizations lead to an optimized environmental impact for the finally used structural component.

The next step in this design approach is to consider the service life (see (Figure 6)). Ideally, a probabilistic design for service life is carried out. The diagram at the bottom left in (Figure 6) shows the result of such a design, whereby the reliability index given on the y-axis decreases with increasing time under service. At the end of the defined service life, the given reliability limit state is reached.

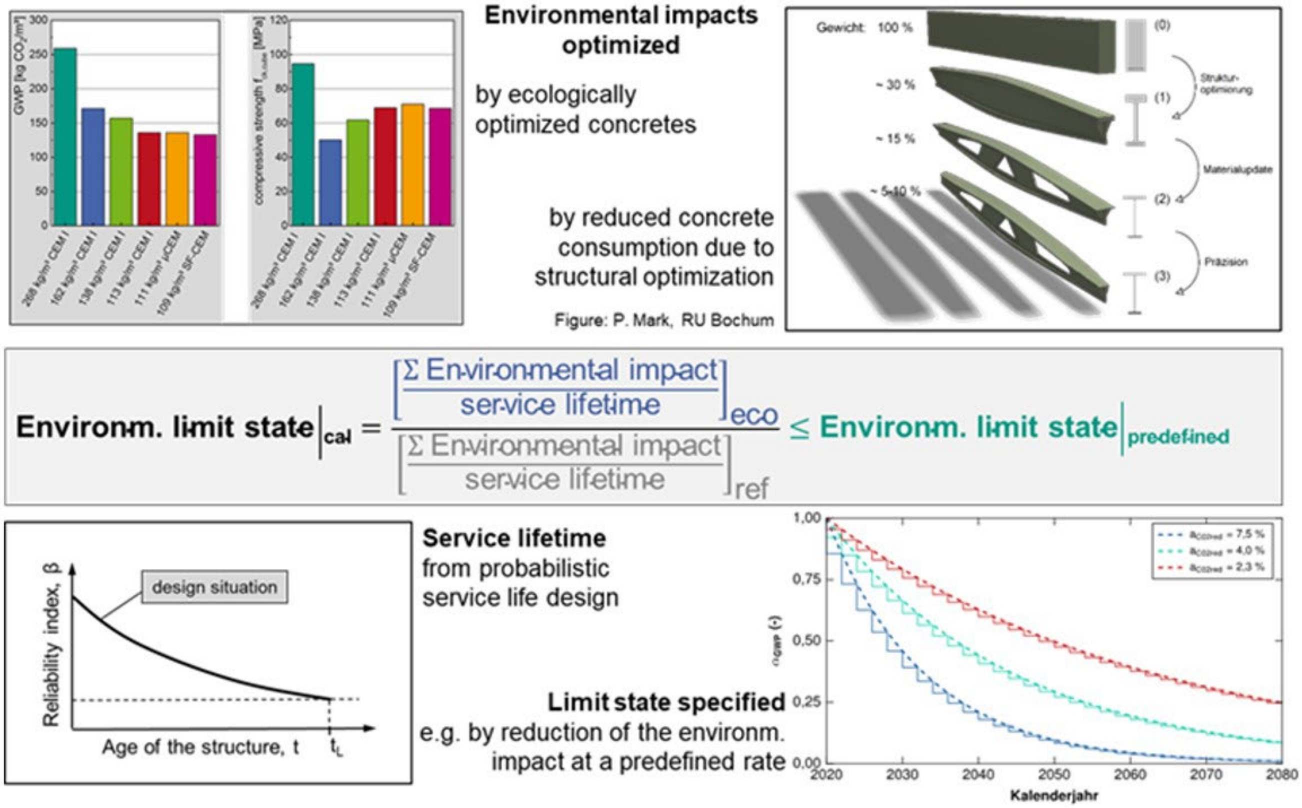

Figure 6. Example for the design of concrete members by means of the design equation for sustainability as given in (fib Model Code, 2023)

In the last step of design, the limit state for sustainability must be defined. Due to the structure of the design equation, this limit state can be expressed by any number between 0 and 1. Since with regard to the reduction of CO_2 emissions, the desirable limit state of zero emissions cannot be achieved immediately but rather through a degressive development over time, the assessment can be based on corresponding progressions, taking into account the calendar year. The diagram at the bottom right of (Figure 6) shows the curves for three different annual reduction rates for CO_2 emissions.

This concept for sustainability assessment and design presented here is innovative and new. It can be considered as a basis and framework, and as a starting point for further developments. So far, there is no practical experience in the application of this concept. It is to be expected that the application of this concept in the practice of concrete construction will certainly lead to further improvements in the coming years.

5. Concluding considerations

The concrete construction industry faces significant challenges, which primarily consist of reducing the CO_2 footprint of concrete construction without negatively influencing the technical performance and the superior durability of the produced structures. Even though environmentally optimized concretes are readily available today and techniques to produce much slimmer and mass reduced structures have been proposed, these techniques are rarely implemented in everyday construction as suitable incentives and the necessary knowledge are lacking.

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Nevertheless, it is the designer who plays the decisive role in the way to an efficient reduction of the GWP and the protection of the global climate. The design aids proposed with (Equation 1) and (Equation 2) are initial approaches, still to be further developed, for demonstrating the sustainability of materials and components. However, such proofs will only find their way into practice when a core problem that still exists today is overcome. This is because nearly all measures that lead to a significant improvement in sustainability are ultimately still associated with higher costs. As long as this does not change, the cost pressure in the competitive economic environment means that the desired, major progress will fail to materialize.

Ultimately, this deficit can only be eliminated by enforcing sustainable measurement with normative specifications. Since the CO_2 emissions associated with the production of concrete components can be calculated with the tools available today, one concept could be, for example, to price the CO_2 emissions, as is currently already the case with emissions trading. It will be interesting to see what solution politicians come up with in this regard. The necessary tools have already been provided by the research community.

6. Notes on Contributors

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