GREEN CONCRETES – PRINCIPLE DESIGN APPROACHES FOR MATERIALS AND COMPONENTS

Dedicated to Prof. György L. Balázs
for his 65th birthday

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This article deals with the evaluation and design of eco-concretes (green concretes) and structural components made from them. Such concretes are characterized by a pronouncedly reduced CO_2 *footprint compared to conventional structural concretes made with Portland cement clinker. After an introduction to the sustainability problems of today's structural concretes, the basic approaches to the development of sustainable concretes are presented. The specific parameter Concrete Sustainability Potential is introduced, which combines the main effecting parameters environmental impact, service life (durability) and performance (strength). An overview in possibilities available today for producing green concrete mixtures is given. Certain emphasis is placed on eco-concretes, in which a large proportion of the cement is replaced by rock powders. Further, 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: green concrete, concrete composition, sustainability, design.

1. SUSTAINABILITY PROBLEMS ASSOCIATED WITH TODAY'S CONCRETE

Concrete is by far the most important building material of the modern industrial age. It 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 decisive advantages of concrete - comparatively high strength and durability combined with high availability in huge quantities and cost-effective production anywhere in the world - are not even remotely matched by any other building material.

However, a very unfavourable factor is the high CO_2 emission associated with concrete production which results mainly from the cement manufacturing. It was not until the turn of the millennium 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, for example, by energy production through the burning of fossil fuels 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 tremendously 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 levels can be reached. This target was set in the Paris Agreement of 2015 in order to prevent the worst effects of the climate change. It is therefore not surprising that many strategies have been developed, in particularly in the past decade, to significantly reduce the CO_2 footprint associated with concrete construction.

In the subsequent chapters the basic approaches to the development of sustainable CO_2 reduced concretes are presented. As an important tool, the concrete sustainability potential is introduced which combines the governing parameters environmental impact, service life (durability) and performance (strength). Further, an overview on the possibilities available today for producing green concrete mixtures is given. Hereby emphasis is placed on 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 components made from it.

2. APPROACHES TOWARD SUSTAINABLE CONCRETE

In order to meet the requirements of sustainability with regard to concrete as a building material, at first sight the concrete composition must be fundamentally changed. In particular the content of Portland cement clinker, which is associated with extremely 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, the reduction of the CO_2 emissions alone cannot be addressed. For example, if one single high CO_2 emission is associated with a 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. Moreover, high performance and durability are required from the building material itself in the case of structures, which 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 and fib 2023):

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

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* 2023).

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 for structural components.

According to equation (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-mentioned approaches appears reasonable. This is also summarized in the subsequent *Fig. 1*. It also indicates some examples, how to maximize service life and performance, and how to minimize the environmental impact.

Related to the environmental impact, i.e. the use of raw materials with reduced eco-impact, e.g. composite cements, new types of cements (low/no carbon), 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.

As the use of Portland cement is indispensable for producing structural concrete today, the question arises what the most efficient way is when applying this binder in view of minimizing the environmental impact. In this context a concrete data evaluation by 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 *Fig. 2*). The decreasing binder intensity with increasing compressive strength indicates that the use of Portland cement is the more efficient (sustainable) the higher the strength is. This is the 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.

Fig. 2 also indicates that for normal and low strength concrete the amount a cement used for these concretes is not necessary for the reason of strength, however, certainly for workability and durability reasons. This means that cement may be saved for these kinds of concrete, 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.

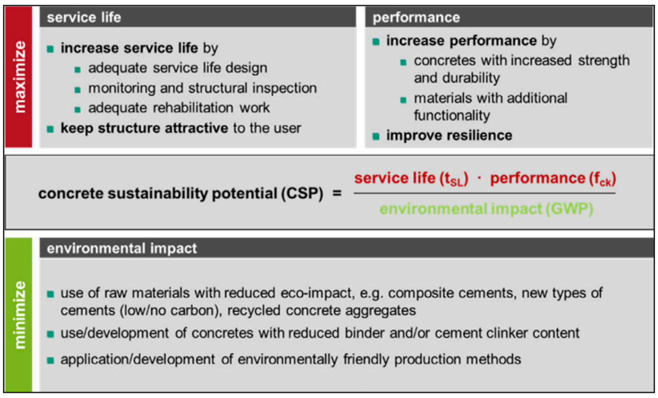
From *Fig. 2* the general conclusion may be drawn that the reduction of the binder content of ordinary strength concrete and the use of high strength concrete lead to a sustainable use of concrete. The concept of reducing the binder content for ordinary structural concrete while keeping its advantageous technical properties is further analysed in chapter 3 of this paper.

3. GREEN CONCRETE MIXES

3.1 General approaches

In order to meet the requirements of sustainability with regard to 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

Fig. 1: Overview on approaches and tools to develop sustainable concretes



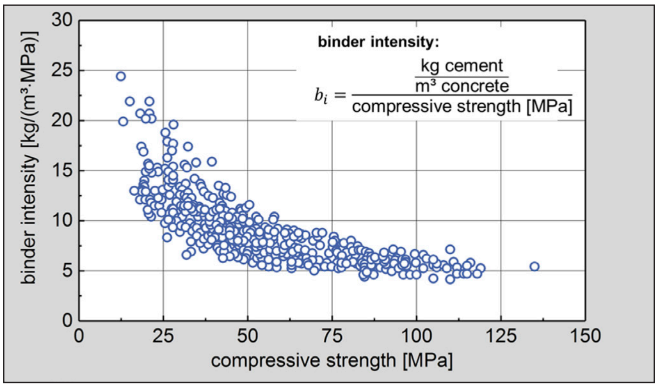
- **increase service life** by
  - adequate service life design
  - monitoring and structural inspection
  - adequate rehabilitation work
- **keep structure attractive** to the user

- **increase performance** by
  - concretes with increased strength and durability
  - materials with additional functionality
- **improve resilience**

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

- use of raw materials with reduced eco-impact, e.g. composite cements, new types of cements (low/no carbon), recycled concrete aggregates
- use/development of concretes with reduced binder and/or cement clinker content
- application/development of environmentally friendly production methods

Fig. 2: Efficiency of the use of binder depending on the strength of structural concrete according to (Damineli et al 2010)



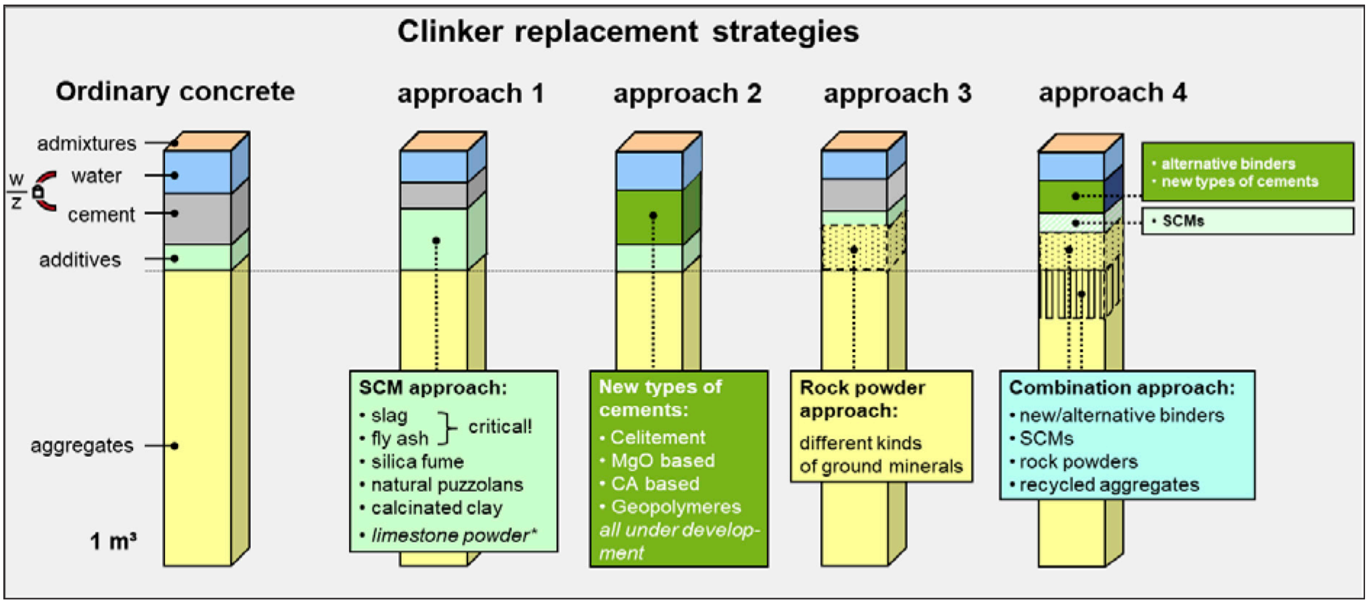


Fig. 3: *Strategies and examples for the reduction or replacement of Portland cement clinker for the production of structural concrete*

inert fines of aggregates is also a very promising approach to significantly reduce the carbon footprint of concrete mixes.

Fig. 3 summarizes the different strategies for clinker replacement by subdividing these strategies into four different kinds of approach. 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.

Approach 1 (see *Fig. 3*) 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 critical. BFS is a by-product of steel production. Therefore, its availability is limited and BFS may never replace PC 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. Silica fume (SF) is also by-product having a very limited availability in the market. The other SCM mentioned in *Fig. 3* (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 *Fig. 3*) assumes that Portland cement clinker will be completely replaced by new types of cements/binders. In addition to the product Celitement 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 *Fig. 3*) 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 *Fig. 3* is a combination of the approaches 1 to 3 with the additional use of recycled aggregates for concrete production.

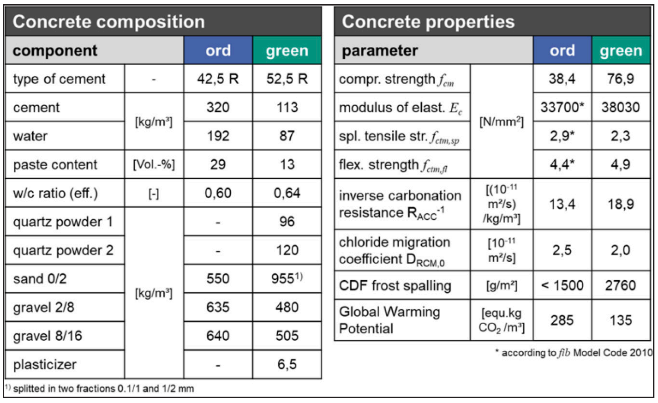
An alternative to these four approaches is the CO_2 avoidance strategy by carbon capture and storage (CCS) or carbon capture and use (CCU) concepts being under development in some countries. These concepts allow the conventional production of PC as the associated CO_2 emissions are captured by applying 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 in the focus of the current research. This research is entering new areas what is not the case with the cement industry approaches, as it has to stay within the framework of established regulations with its modified binders in order to be able to serve the needs of the market.

3.2 Green concrete by the rock powder approach

As already mentioned above, approach 3 was scientifically investigated in more detail by the author (Müller et al 2016 and 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 or may be produced anywhere in the world.

However, this change in the composition of concrete, i.e.



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	955¹⁾
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

Fig. 4: Comparison of green concrete (cement replacement by rock powder) and ordinary concrete C30/37 – concrete compositions (left) and concrete properties (right)

the replacement of cement by 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.

Fig. 4 summarizes important results of the extensive investigations given in (Müller, 2019). It shows the composition (left) of a standard structural concrete and a green concrete produced according to approach 3. The right part of *Fig. 4* 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 a 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 an ordinary concrete (here GWP considers all materials and processes).

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 Fig. 4). 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.

3.3 General consideration in view of applying green 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 designing 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. DESIGN TOOL FOR CONCRETES AND COMPONENTS

The Concrete Sustainability Potential as defined with 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 a concrete for sustainability, equation (1) must be reformulated for various reasons. This also applies for 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 or strains are. Hence, relative values should be determined in which 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 and thus canceled for the design for sustainability.

Taking the afore-mentioned considerations into account, the general format for verification of concrete environmental performance is proposed with equation (2), which defines a limit state, see (fib 2023):

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

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 criteria ($ELS_{predefined}$) is fulfilled.

For practical application, equation (2) can also be simplified, for example by focusing the limit state consideration exclusively on the of CO_2-eq emission. In such case, ΣEI = CO_2-eq mass per cubic metre [kg/m³] of concrete and SL = 1.0. For more details, see (Haist et al 2022 Oslo, and Haist et al 2022) and (fib 2024 in prep.).

Fig. 5 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 *Fig. 5,* diagram top left. As a result,

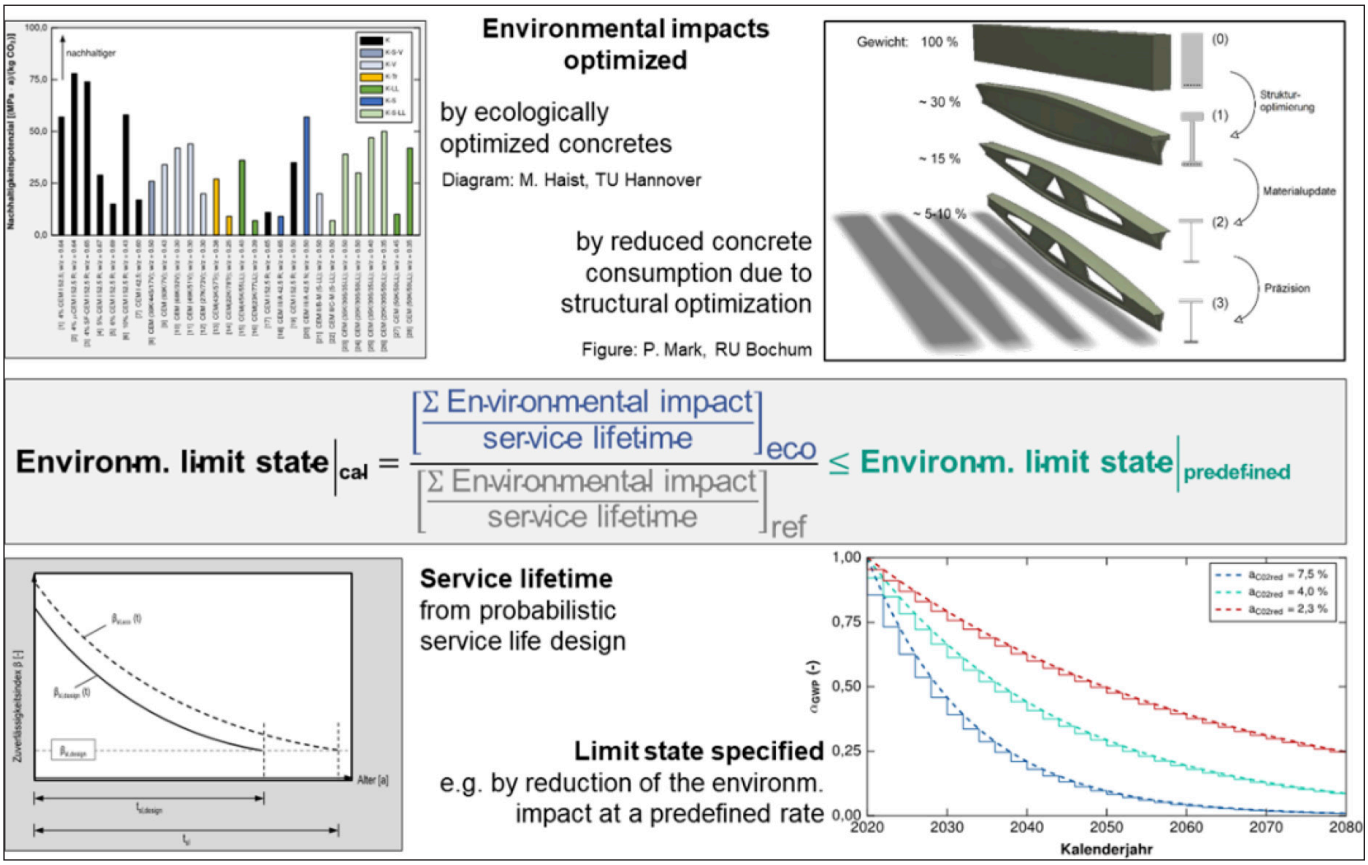


Fig. 5: Example for design of concrete members by means on the design equation for sustainability as given in (fib 2023)

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 consumption (see *Fig. 5*, 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 *Fig. 5*). Ideally, a probabilistic design for service life is carried out. The diagram at the bottom left in *Fig. 5* 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.

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 the time, the assessment can be based on corresponding progressions, taking into account the calendar year. The diagram at the bottom right of *Fig. 5* 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 in 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 every day construction as suitable incentives and the necessary knowledge are lacking.

Nevertheless, it is the designer who plays the decisive role on the way to an efficient reduction of the GWP and such 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 that 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.

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