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Sustainable Concrete Structures – Design Approaches for Materials and Components

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Changes in the current use of concrete materials and design approaches are mandatory in order to comply with the requirement for sustainable future concrete structures. On 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 with Portland cement clinker. After an introduction to the sustainability problems of today's structural concretes, the basic approaches for the development of sustainable concretes 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 in 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 cement is replaced by rock powders. Further, adequate service life design for concrete and concrete components is indicated, as the corresponding calculations play a decisive role in view of sustainable concrete structures. 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, service life design, sustainability.

1. Problem statement

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 up to nowadays not even remotely matched by any other building material. For this reason, concrete became 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.

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 when the 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 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 level 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.

When thinking of a solution to this sustainability problem, a first idea could be to strive for a tremendous reduction of the use of concrete. However, as can be seen from the above, this is absolutely impossible. Such an approach would cause fundamental economic problems for the entire world.

The second idea 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 idea is also ruled out from the outset.

The above leaves the third solution consisting of retaining conventional cement production but capturing the CO_2 emissions. The technology of capturing CO_2 is well developed since a couple of years. However, currently it is only being tested in a few pilot projects in cement production. If this technology proves successful, it will probably last decades before every cement plant in the world has been converted accordingly. Further, it must also be accepted that the price of cement will rise significantly. At present, it is roughly assumed that the price of cement will double.

In view of the 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. Various strategies can be adopted, which are discussed in this article.

First, as an important tool the Concrete Sustainability Potential is introduced that combines the governing parameters environmental impact, service life (durability) and performance (strength). Further, an overview on 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.

As the parameter service life of components and structures plays a decisive role in the context of sustainability associated with the use of concrete, the procedure of an adequate service life design is indicated as well. 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. The sustainability potential associated with the use of concrete

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 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 CO_2 emissions alone cannot be addressed. For example, if one single high CO_2 emission is associated with the production of 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. 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 [1, 2]:

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

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 [2].

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.

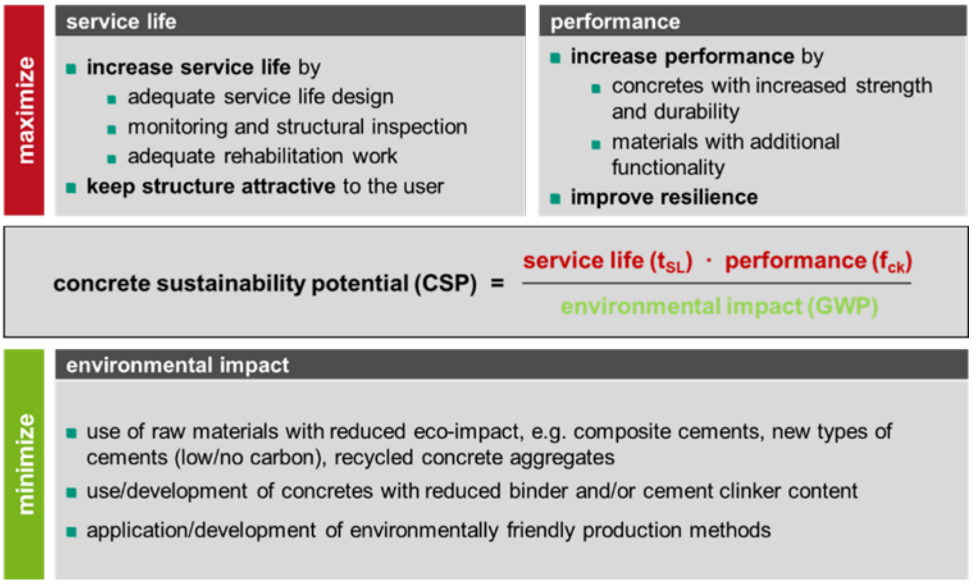


Fig. 1: Overview on approaches and tools to develop sustainable concretes

Figure 1 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 of time, for example in industrial construction, a significantly lower quality of concrete is acceptable than for structures which are used over long periods of time, as is the case with structures of great economic importance (tunnels, bridges, dams). Note that currently the higher the quality of concrete the higher are 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 cements, new types of cements (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.

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 [3] is very revealing. They have defined a so-called binder intensity, and have plotted this binder intensity over the compressive strength (see Fig. 2).

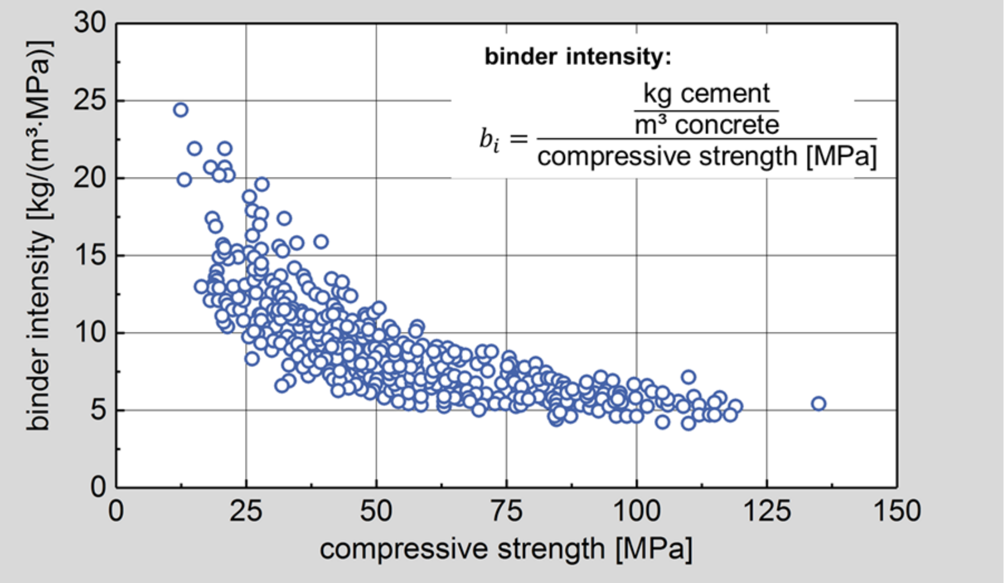


Fig. 2: Efficiency of the used amount of binder in typical structural concretes depending on the strength of concrete [3]

The decreasing binder intensity with increasing compressive strength, as may be depicted from Fig. 2, 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.

Figure 2 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 Fig. 2 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. Design of sustainable concrete mixes

3.1 Approaches for sustainable mixes

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

Figure 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.

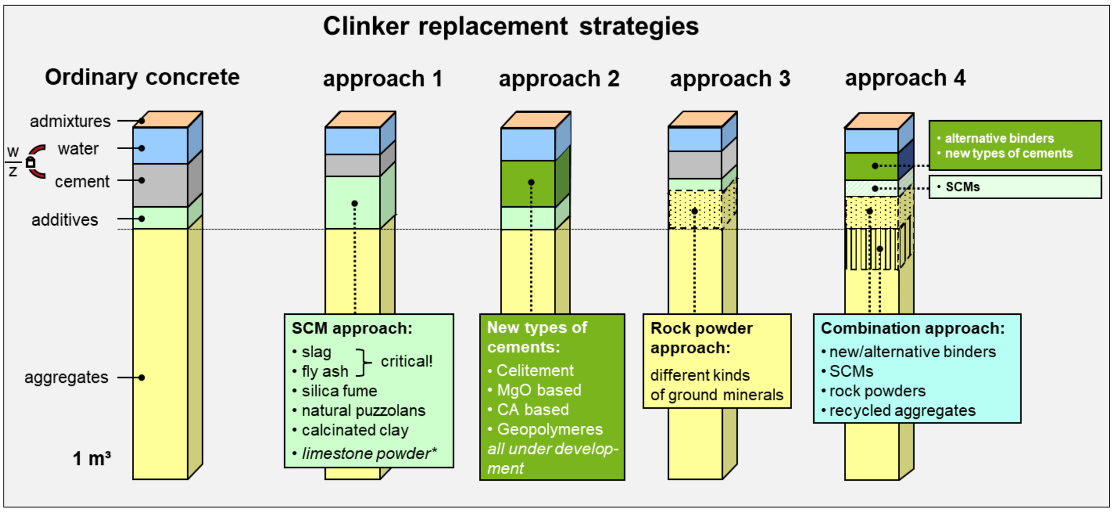


Fig. 3: Strategies and examples for the reduction or replacement of Portland cement clinker for the production of structural concrete

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 in time. 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. The amount of recycled aggregates may cover a large part of the total aggregates.

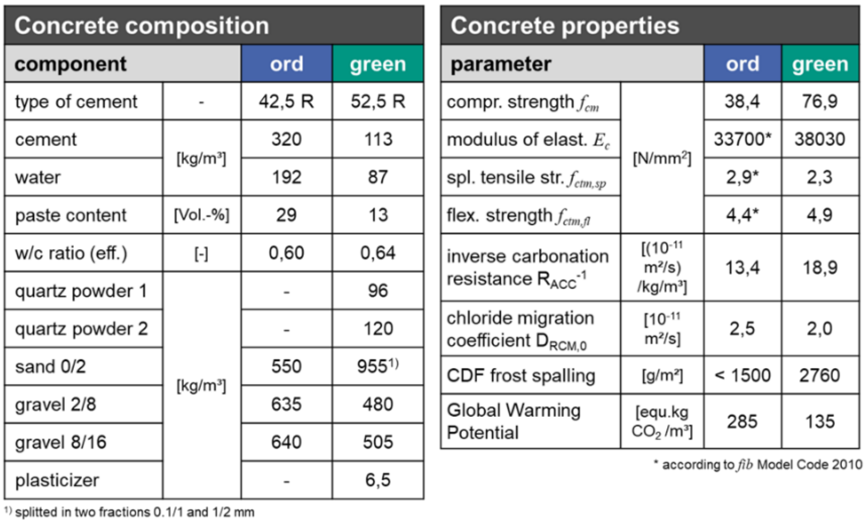
An alternative to these four approaches is the CO_2 avoidance strategy by carbon capture and storage (CCS) or carbon capture and use (CCU) concepts being under development in some countries. These concepts allow the conventional production of PC as the associated CO_2 emissions are captured by applying 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 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 and codes with its modified binders in order 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 [1, 4]. 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 in large amounts anywhere in the world.

However, this change in the composition of concrete, i.e. 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. Note that superplasticisers have been chemically design in order to work with cement particles and not with fine aggregate particles which have different molecular surface properties.



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

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

Figure 4 summarizes important results of the extensive investigations given in [4]. 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 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 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 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. Application of service life design approaches

4.1 Basic considerations and overview

The service life of concrete structures is a decisive parameter with regard to the sustainable use of concrete (see also Eq. 1). The reason for this is that the use of concrete is inevitably associated with critical emissions and the use of natural resources. In other words, the less new concrete is used, the less adverse emissions are produced. It is therefore sustainable if the service life of existing structures is extended and new buildings are not built. On the other hand, social and economic development requires new and needs-oriented concrete structures.

Taking into account the durability of concrete, emissions and the consumption of resources increase significantly when the planned service life of a structure increases. It is therefore crucial to select the concrete composition in such a way that the durability achieved for the concrete corresponds to the intended service life. This applies both to a long service life, as is the case with large infrastructural structures (e.g. tunnels, bridges, dams), and to a planned short service life of a concrete structure, as is often the case for industrial constructions.

As for sustainability reasons the concrete composition must be adapted to the planned service life for a construction with concrete, it is not possible to apply the currently valid guidelines [5] because the specifications/requirements are designed for a fixed service life of 50 years. In addition, the information on the effecting/environmental conditions and the material properties/concrete compositions is only given in verbal form and characteristic values in tables, and is not described by mathematical-physical time functions.

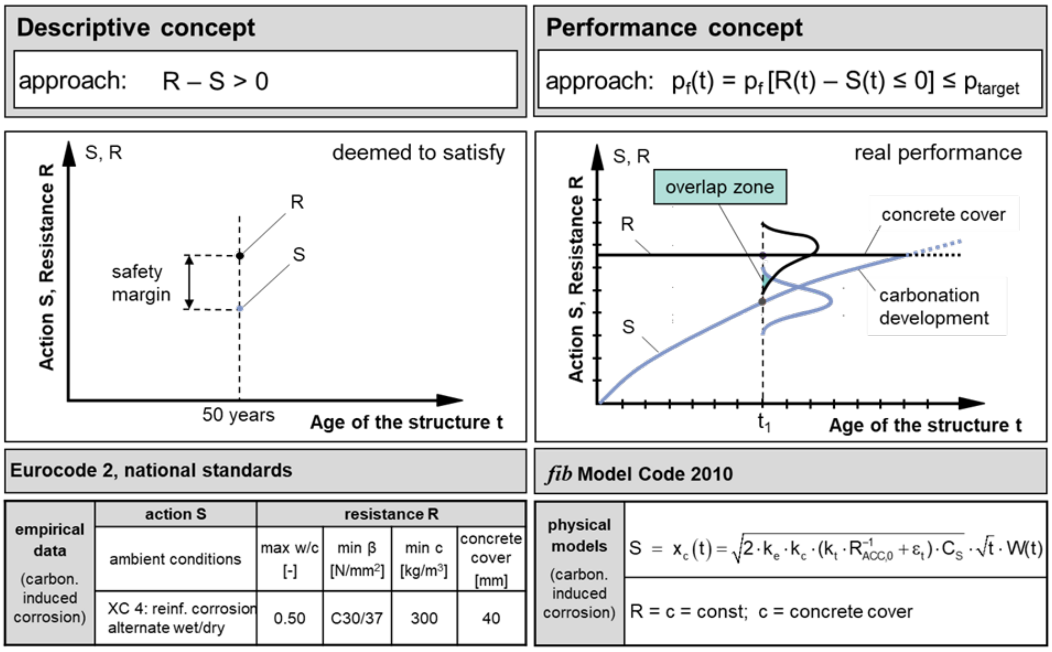
The required material laws or degradation models, respectively, which describe the loss of durability, i.e. the decreasing resistance to the environmental loads in mathematical-physical form, depending on age and environmental conditions, are provided in the fib Model Code 2010 or the fib Model Code 2020. They can be used, for example, to specify specific lifetimes/usage periods and to calculate from this information the corresponding requirements for the concrete properties or the concrete composition, respectively.

4.2 Principle and methodology of service life design

In the engineering design for service life, actions (E) and resistances (R) are related to each other in mathematical form, analogous to a static-constructive design. The actions are environmental conditions or exposures that are divided into classes. The resistances are partly structural requirements (e.g. concrete cover), but in particular the material properties. They are described either by concrete technology parameters (e.g. water/cement ratio, cement content) and minimum design requirements or corresponding material parameters (e.g. diffusion coefficient). The consideration of failure probabilities is indispensable. The applied probabilistic methods in combination with the description of the concrete behaviour by means of degradation models enable the solution of complex practical problems.

The two different basic concepts for the design for service life are illustrated in Fig. 5 using the example of carbonation-induced corrosion of steel reinforcement. The conventional or descriptive concept, as it is mostly used in guidelines (e.g. [5] and national application documents), assumes that sufficient durability of the structure over 50 years is guaranteed if minimum or maximum values for the water/cement ratio, concrete strength, cement content and concrete cover are complied with (Fig. 5, left). The choice of limit values for the concrete composition is based on the results of scientific studies in conjunction with many years of experience with the behaviour of concrete structures in practice. In English, this concept is appropriately characterized as "deemed to satisfy" due to the existing uncertainty.

Action and resistance are only specified qualitatively when applying the descriptive concept in the case of a general attack. Therefore, the designing engineer does not know how large the safety margin, i.e. the difference (R - E), actually is. It is also not possible for him to quantitatively estimate how the affecting parameters, e.g. concrete cover or concrete composition, are to be changed if a structure is to be used for only 20 years or 150 years, for example.



empirical data (carbon. induced corrosion)	action S	resistance R			
	ambient conditions	max w/c [-]	min β [N/mm²]	min c [kg/m³]	concrete cover [mm]
	XC 4: reinf. corrosion alternate wet/dry	0.50	C30/37	300	40

physical models (carbon. induced corrosion)	
	$S = x_c(t) = \sqrt{2 \cdot k_e \cdot k_c \cdot (k_t \cdot R_{ACC,0}^{-1} + \varepsilon_t) \cdot C_S} \cdot \sqrt{t} \cdot W(t)$
	R = c = const; c = concrete cover

Fig. 5: Design for durability for carbonation-induced reinforcement corrosion; left: descriptive approach as used in codes (CEN, national) being not suited for the adaption to the real service life in order to optimize sustainability (the age of 50 years is fixed); right: performance approach which allow to consider any particular service life (the age t is a variable parameter)

In contrast, the performance concept, often referred to as the probabilistic approach (Fig. 5, right), enables a quantitative prediction of the changing durability over time. This is also illustrated by the fact that the impact/resistance axis and building age axis can be scaled in the diagram. Impacts and resistances are generally described by time functions. For the selected example of carbonation-induced reinforcement corrosion, the action function describes the progress of carbonation over time. The resistance function is time-constant here because it reflects the concrete cover.

A very important feature of the performance concept is that the respective scatter (see the distribution functions shown in Fig. 5, right) must be taken into account for the action and resistance functions. With increasing time, there is a growing overlap of the scattering curves and thus an increasing probability of failure or corrosion p_f.

The design process is summarized in Fig. 3. In the upper part, the governing functions are given. The values of the probability of failure $p_f(t)$ are converted into reliability indices $\beta(t)$, which is merely a mathematical operation. The greater the probability of failure or the area of overlap (= extent of corrosion) according to Fig. 5, the lower the reliability, i.e. the $\beta(t)$ function decreases monotonically with time, as shown in Fig. 6 (lower part).

In a design, the desired service life (t_L value) and the permissible probability of failure at this point in time are taken from guidelines or specified by the owner of the structure. The curves for the action and the resistance can be shifted accordingly or dimensioned in such a way that the desired limit state, i.e. the desired combination of service life and probability of failure, is exactly fulfilled. This ensures that the best possible sustainability is achieved with regard to the use of concrete.

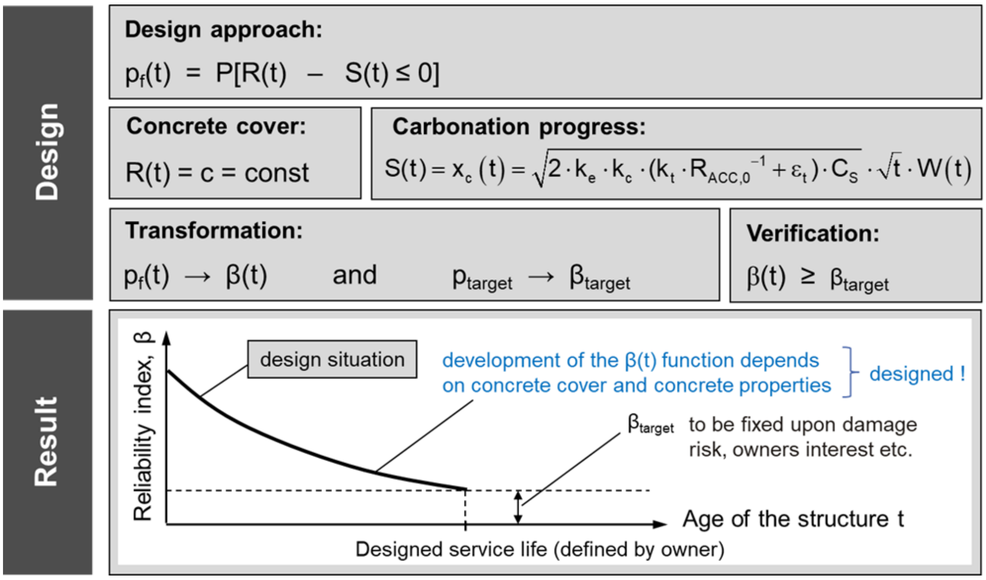


Fig. 6: Principle of probabilistic service life design for the example of carbonation induced corrosion

A fully probabilistic service life design requires both a complete functional description of the action and the resistance for a considered durability-relevant process, and further special statistical analysis tool. Detailed data on the concrete used and the scatter values for the input parameters (see S-function in Fig. 5, bottom right), i.e. the type of distribution function, mean value and standard deviation, must be known.

4.3 Further aspects

From the point of view of the methodology and the required input parameters, the two concepts compared in Fig. 5 represent two extreme cases of durability design. To date, the information required for a fully probabilistic service life design is only available for carbonation and chloride-induced reinforcement corrosion [2, 6]. For all other processes of degradation of concrete, there are essentially only descriptive design concepts based on findings from scientific investigations and experience. In view of the complexity of the various degradation processes, it will probably last decades before full probabilistic prediction models will have been developed for all durability-relevant concrete properties [7].

Between the two basic concepts shown in Fig. 5, various intermediate stages can be located, the development of which is currently being worked on intensively [7]. It is becoming apparent that the descriptive concept in national and international guidelines (Fig. 5, left) will be replaced by extended concepts based on partial safety factors, possibly supplemented by performance tests. Design engineers will have design tables or diagrams at their disposal that enable simple engineering design for durability, see also [8].

5. Design tool for sustainability of 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 cancelled 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 [2]:

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

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.

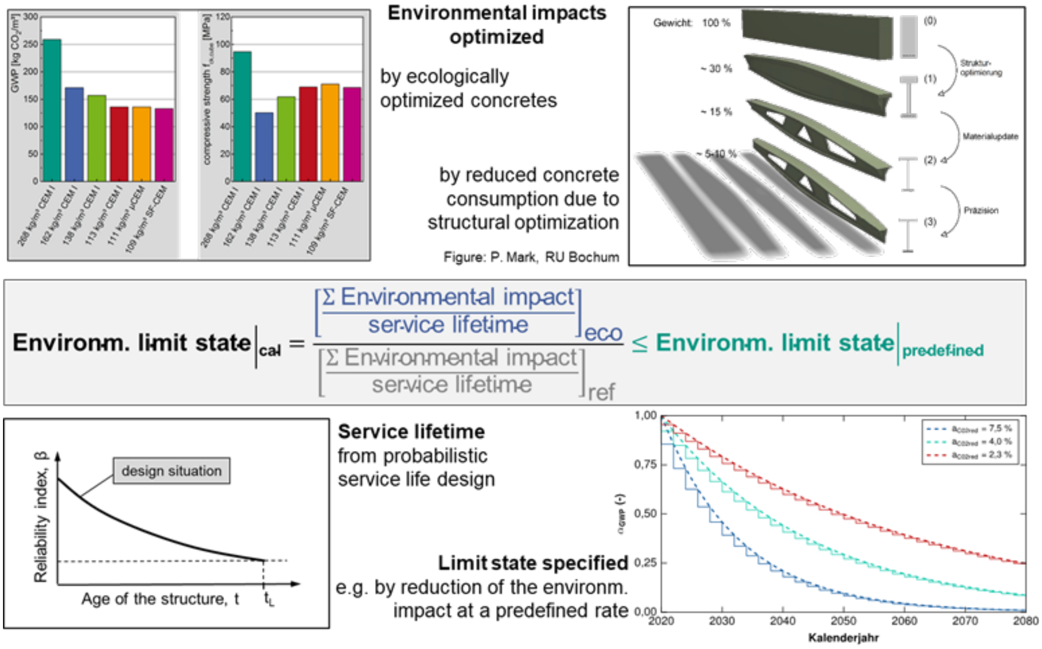
The index *ref* indicates the value calculated for a reference concrete. The index *eco* indicates the value calculated for a concrete for which an optimization has been carried out in such a way that the predefined limit state criteria ($ELS_{predefined}$) is fulfilled.

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/m^3] of concrete and SL = 1.0. For more details, see [9, 10, 11].

Figure 7 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. 7, 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 consumption (see Fig. 7, 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. 7). Ideally, a probabilistic design for service life is carried out. The diagram at the bottom left in Fig. 7 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. 7 shows the curves for three different annual reduction rates for CO_2 emissions.



$$\textbf{Environm. limit state}\Big|_{cal} = \frac{\left[\frac{\Sigma\ \text{Environmental impact}}{\text{service lifetime}}\right]_{eco}}{\left[\frac{\Sigma\ \text{Environmental impact}}{\text{service lifetime}}\right]_{ref}} \leq \textbf{Environm. limit state}\Big|_{predefined}$$

Figure: P. Mark, RU Bochum

Fig. 7: Example for design of concrete members by means on the design equation for sustainability as given in [2]

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.

6. 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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