Concrete, Sustainability and Limit States

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Abstract. Efficient sustainability management of concrete structures requires the use of tools which allow material, technological and construction variants to be quantified. The present contribution, apart from discussing the issue of sustainability of concrete structures, focuses on the quantification of concrete resistance to degradation. An indicator expressing quality, with regard to sustainability, is determined using information on concrete performance characteristics, service life and eco-costs, enabling the quantification and comparison of various cases. Cradle-to-gate system boundary and the full probability method are used. The aim is to propose a suitable methodology which can simplify decision-making about the design and choice of concrete mixes from a wider sustainability perspective, as an extensional and integrating approach to evaluating load-bearing capacity and durability. Two case studies of probabilistic sustainability quantification are shown using sustainability potential indicators for two different definitions of service life (due to carbonation of concrete and freeze/thaw effects), considering also the concrete performance’s and impact on the environment.

1. Introduction

Sustainability approach is a key general principle to be considered in any human activity including design, construction process, operation, maintenance and repair of any structure – including any concrete structure. Concrete is the most common construction material in the world. Because of this, concrete puts a significant strain on the environment – especially in terms of CO₂ emissions. Nevertheless, since it indisputably possesses numerous advantages, there is little doubt that concrete will remain in use as a main construction material well into the future. It is thus evident that enhanced technologies and procedures for designing and/or assessing concrete structures need to be sought and developed.

General principles related to sustainability in civil engineering are described in ISO 15392 [1] – Sustainability in building construction. The purpose of sustainable design is to reduce the negative impacts and to improve the benefits for the society, environment and the economy. ISO 13315 [2], [3] Environmental management for concrete and concrete structures, aims to provide the basic rules on environmental management for concrete and concrete structures. The standard is meant to help with mitigating the environmental impacts resulting from concrete-related activities.

Sustainability is a rather complex subject that must be considered from the very beginning of construction. Webb and Ayyub [4] summarized definitions available in different contexts and introduced requirements and working sustainability definitions for constructions.

According to [1] sustainability measures consider three primary aspects (pillars): social, environmental and economic, pertaining to a relevant system boundary, i.e. cradle-to-grave. Two domains of definition...
can be utilized: general and construction. The first, general definitions include any definition that does not apply to a specific sector. They define sustainability in a rather broad context. The other domain – construction definitions – deal with more specific situations, e.g. with the sustainability of building structures. Also, sustainability metrics and indicators should be mentioned in this context. According to [4] construction-based indicators can be classified at the following levels:

- Scale: global, regional, national
- Country or organization
- Pillar: social, environmental, economic
- Aspect: materials, energy, water, air, financial, health or others
- Phase: design, construction, operation, maintenance, demolition. (Note the set of applied phases can determine the system boundary used).

There is a need for the implementation of sustainability criteria into a performance-based approach [5] which is currently at the centre of research all over the world, in particular in the activity of fib Commission 7 Sustainability [6], [7] and fib Commission 10 preparing Model Code 2020 with a focus on sustainability. In this context the issue of limit state has to be discussed as well and adjusted in a relevant way considering the design of reinforced concrete structures; it is closely related to sustainability assessment and its quantification. This approach can be utilised in the design and assessment of concrete mixes quite broadly, i.e. not only with regard to load-bearing capacity or durability, as is currently common in civil engineering.

The goal of the present paper is to propose a suitable decision-making methodology for working with concrete with special focus on sustainability aspects. It deals with material aspects during design and construction, analysing the sustainability of a concrete mix. The presented approach is based on Müller [8], [9], who described three sustainability pillars in terms of three quantities: performance, service life and environmental impact expressed in the form of the Building Material Sustainability Potential (BMSP). In a normalized form BMSP could be transformed into the indicator $kSB$ which enables quantification with respect to environmental conditions and the prospect of suffering degradation [10], [11], as shown further.

The paper presents examples of different concrete types which are subjected to different effects. Utilizing the sustainability indicators $kSB$ the sustainability level can be compared and quantified also within a fully probabilistic approach.

2. Limit state concept from the perspective of sustainability approach

The probability-based limit state (LS) design is a common approach in civil engineering practice today, and is described e.g. in the international documents ISO 2394, EN 1992-1-1 and fib Model Code 2010 [12]. The structural ultimate limit state (ULS) and serviceability limit state (SLS) are commonly utilized in current practice either as part of the semi probabilistic format (partial factor) or, in the fully probabilistic approach. Considering degradation effects, exposure conditions, and using ULS and/or SLS, the service life $L$ can be assessed as well. This can be performed with a suitable model analysis of degradation effects with effective software tools [13], [14], which offers a number of different numerical degradation models in a probabilistic format, producing statistical, sensitivity and probability results. Generally the analysis is governed by a probability condition which in its general form reads:

$$P_f = P\left[A(t) \geq B(t)\right] < P_d$$  \hspace{1cm} (1)

where $P_d$ is the design probability (target, limiting, required), $t$ is time, $A$ is the effect of the action being analysed and $B$ is the barrier. Generally, both $A$ and $B$ are time dependent and hence the probability of failure $P_f$ is time dependent as well. The combined effect of both structural performance and ageing should be considered wherever relevant. Note the index of reliability $\beta$ is frequently utilized in the practice of structural design instead of the probability of failure $P_f$ – see e.g. ISO 2394.
Service life \( L \) is usually defined as a period of time after installation during which technical, functional or other requirements are met or exceeded. Different types of service life can be distinguished: the technical service life, functional, economical and aesthetic (or obsolescence) service life. However, when evaluating the sustainability of reinforced concrete structures it is advisable to work with the definition provided by the fib Model Code 2010. It describes service life (in years) using the relevant limit state (LS) and associated target level of reliability \( P_d \). This expresses the technical service life, i.e. the design or remaining service life (depending on whether a new or existing structure is being evaluated). This type of limit state and the limit probability value are critical and in order to determine them it is necessary to model the degradation of materials over time or, less effectively, estimate the service life via the Factor method (ISO 15686) or by expert judgement.

The most commonly used concrete structure design today is performance-based according to fib Model Code 2010 [12]. Sustainable target value design can be briefly expressed as a comparison of sustainable capacity vs. sustainable impacts. This requires a new class of limit states – apart from engineering (or structural) ones, sustainability limit states have to be specified as well, as mentioned in [15] and also in fib Model Code 2010, where:

(i) Section 7.10.1.2 dealing with environmental performance reads “... it shall be confined at the design stage that the environmental performance required for the structure is satisfied. This is undertaken using a Life Cycle Analysis. ... Verification: Environmental performance of a concrete structure shall be verified by confirming that the retained performance (R), defined by using appropriate indexes with regard to environment, is larger (or smaller) than the set value (S) of the relevant performance requirement.” Note that environmental performance is also linked with e.g. global warming potential, ozone, emissions of acid-generating gases, eutrophication, waste storage, etc. Ecological criteria associated with evaluating the impacts of concrete-based structures on the environment include mainly: bound CO\(_2\), SO\(_2\), NO\(_x\) emissions, bound energy, the consumption of non-renewable resources, the consumption and pollution of water, waste, but also potential recyclability should be taken into consideration. Since only some of these components can be used for each of the many conceivable different cases thus only the influence of CO\(_2\) is usually considered.

(ii) Social performance is described in a similar way in section 7.10.2.2: “... the retained (social) performance (R)... regarding the impact on society is larger (or smaller) than the set value (S) of relevant performance requirement.” In this respect, safety, serviceability and durability are also social aspects [16], [17]; i.e. parts of social responsibility (Life Cycle Social Performance, LCSP), and therefore SLS, ULS and L fall also into this category (albeit usually being understood and utilized as the basic criteria of safety and serviceability as well, i.e. engineering criteria according e.g. to fib Model Code 2010).

All these factors have to be verified when performing a life cycle analysis, i.e. by considering the entire life of the structure based on ISO 14040 [18]. A new, advanced fib Model Code 2020 is to be published in 2020 complete with an implementation of sustainability approach as is stated in [5]: “MC2020 will take sustainability as a fundamental requirement, based upon a holistic treatment of societal needs and impacts, lifecycle costs, and environmental impacts.” As for concrete structures specifically the future development of the sustainability approach, prospects and consequences are explained in more detail in [17].

The limit state approach is not yet commonly used for sustainability analysis and relevant limit states are not being employed in practice. A recent paper [15] discusses this, unfortunately only verbally without formulating relevant limit state equations. Such a limit state approach has to be based on the probabilistic approach combined with the life cycle approach considering a very broad and subjective sustainable development. It is a highly complex matter, as besides the construction LS, the sustainability LS (environmental and social) need to be addressed as well; it also comprises the main goal – to determine the global pollutant reduction targets which is mainly the role of policy-makers and environmental specialists. A wealth of literature dealing with this topic can be found elsewhere (see e.g. a concise text [19] and basic directory [6]). Analogous to structure failure probability, the probability that the cumulative impacts over the timeline of the construction and repair of a concrete structure do not meet the target reductions in cumulative impacts as compared to the status quo, the current cumulative impacts can be
understood as a sort of sustainability limit state [20]. At the same time the service life and/or financial factors must be considered as well. Broadly speaking, an LS by which sustainability can be assessed has not yet been identified. All this greatly complicates the sustainability design of structures and places obstacles in practice. Civil engineering sorely needs tools for prioritization and decision-making.

It should be mentioned that a relatively large number of investigations all over the world have dealt with the multi-criteria evaluation of buildings or large structures and assessment of their sustainability. Analyses and assessment of sustainability, as a rule, are hampered by uncertainties which can usually devaluate the results and their applicability to a certain extent; moreover, methods, such as obtaining the opinion of a group of experts, are used, which can be rather time-consuming and costly. Therefore some simpler alternatives are sought, although they are only being utilized for more limited purposes, e.g. for aspects of material only. Also, environmental sustainability targets are often expressed as a reduction from baseline emissions and an achievement of reductions in environmental impact indicators as compared to the status quo design can likewise be applied. The probability of failing to meet a reduction goal by implementing an alternative design is discussed in [20] where a relevant limit state condition is presented. This example implies that only one sustainability pillar is involved (environment) in such an assessment; insufficiencies of this sort can be found quite often – e.g. durability is often left out of in sustainability studies [21].

3. Sustainability potential indicator

Considering the above described problems it might prove useful to focus attention first on the evaluation and comparison of simpler problems, however with sustainability defined in a complex way. A possible approach to making an approximate assessment of the sustainability potential could be based on the Building Material Sustainability Potential (BMSP) defined by Müller in Eq. (2) see [8], [22].

\[
BMSP = \frac{\text{performance} \times \text{service life}}{\text{environmental impact}} = \frac{R \times L}{E} \quad (2)
\]

Material sustainability (concrete specifically) can be quantified for practical purposes using all the material aspects together by normalized Eq. (2) in the form according to Eq. (3), thus creating a sustainability potential indicator \( k_{SB} \). Quantities \( L \) (service life), \( R \) (performance) and \( E \) (eco-cost) are there divided by arbitrary reference values \( L_{ref}, R_{ref} \) and \( E_{ref} \), thus leading to the dimensionless quantity \( k_{SB} \) whose value usually approximates 1.0.

\[
k_{SB} = \frac{R}{R_{ref}} \frac{L}{L_{ref}} \frac{E}{E_{ref}} \quad (3)
\]

The authors of the present paper have been focusing on such sustainability quantification connected with the use of various types of concrete with regard to their resistance to degradation – e.g. [10], [11].

Note that all three pillars of sustainability are integrated in \( k_{SB} \) as both social and economic effects are associated (however partially indirectly) with service life and performance (limit levels of reliability measures and service life are, in relation with different conditions, stated in/required by standards). The environmental impact is expressed in the eco-costs (expenditures on measures to be taken so as to reduce environmental impacts to a sustainable level). The procedure can be improved further by using the probabilistic approach, i.e. by considering the input quantities \( L, R \) and \( E \) as random with known probability parameters and distribution, which produces output values of statistical parameters of \( k_{SB} \) and its probability distribution. The FReET-SB is used for this task; it enables the statistical and probability analysis of formula (3), (4) and it is a modification of the fully probabilistic tool FReET [13]. This also enables the evaluation of the probability \( P_{SB} \) with which a certain limit (acceptable) value of \( k_{SB,lim} \) could be exceeded using the limit state equation

\[
P_{SB} = \left[ (k_{SB} - k_{SB,lim}) \leq 0 \right] \leq Pd(t) \quad (4)
\]

Both Eq. (3) and (4) might become useful in the design practice in near future as it is believed that tackling sustainability problems will become more important.
In Eq. (3) the performance $R$ represents e.g. load-bearing capacity, deformability, resistance to degradation or other properties of the material. When analysing concrete mixtures using formula (3), it is often convenient for $R$ to represent compressive strength. Eco-costs $E$ (as mentioned above) are expenditures on measures to be taken so as to reduce environmental impacts to a sustainable level as explained e.g. in [23] and, in more detail, covered in various databases – e.g. the eco-cost database [24] and [25] where components of $E$, i.e. the individual elements (virtual pollution prevention costs, costs of energy, material depletion costs and some others), are listed. However, there is a whole range of other definitions of $E$, and political or local issues are often involved. When evaluating a sustainability potential indicator, service life is determined with regard to the given/chosen type of degradation or/and mechanical loading, and to exposure conditions. Numerical modelling is favourable; a number of models of several concrete degradation effects has been used, specifically the software tool FReET-D [13], [14], in agreement with fib Model Code 2010.

Aside from the evaluation and quantification of sustainability, it is also generally useful to carry out an economic comparison by comparing the cost of the individual implementations (concrete mixes). One way of performing this is having $R$ only represent the acquisition costs of the case being evaluated (money = performance!) and omitting service life. Eq. (2) transforms into the form of a price-type BMSPe

$$BMSPe = \frac{R}{E}$$  \hspace{1cm} (5)

This quantity can be used to compare individual variants in financial and environmental terms, if ecological cost is considered. Note equation (5) is simultaneously an inversion quantity for the “ERV indicator” (Eco-costs/Value Ratio) developed by Vogtländer et al. [23].

4. Comments about the Material Aspect implementation and examples

The above comments about limit states indicate that sustainability analyses of general aspects would require dealing with a number of limit states: structure (e.g. ULS, SLS), environmental and social type. Especially limit states of the last type are not commonly constructed; moreover, a consequence of the number of the limit states involved is the need to apply a multiobjective optimization tool, which is a labour intensive endeavour, although there are many examples in writings on LCA. The present paper concentrates on the sustainability analysis of concrete based on the material level, which is a simpler task. An effective comparison and selection can be achieved with the use of sustainability indicators related to the cradle-to-gate system boundary and analysed in the probability method. However, it should be mentioned there are also some obstacles involved:

Sustainability indicators (3) can be effectively applied as a sustainability measure for the purpose of comparing various concrete mixes under the condition that all cases in a given group of mixes must be considered as being subjected to the same type of exposure and the same deterministic reference values of $L_{ref}, R_{ref}$ and $E_{ref}$ have to be used. This probabilistic evaluation of sustainability of concrete mixes does not cover usage of the structure, repair or rehabilitation – it is merely a cradle-to-gate boundary condition system intended for the selection or optimization of cases of one group and considering their sustainability (note there is the exception of service life $L$ which is supposed to proceed until “the grave”). Note, the applicability of Eq. (3) and (4) is limited, as the values of $k_{SB}$ depend on arbitrarily chosen values of $L_{ref}, R_{ref}$ and $E_{ref}$. Therefore the sustainability level of concretes in the studied group can be assessed according to the order of $k_{SB}$.

Two examples follow:

(i) Example from ISO 13315-4 [26], Annex C is discussed. The concrete structure presented in ISO (concrete A1) is required to show a 30% reduction in CO$_2$, which is achieved by adjusting the formula to contain ground granulated blast furnace slag (concrete B1) as shown in Table 1. The required reduction of CO$_2$ is met in this way, unfortunately without taking durability into consideration. The authors added the results of a service life analysis by modelling concrete carbonation, applying the FReET-D tool [12], option RC LifeTime, using the model created by Papadakis et al. [27]. The following input data were
applied: exposition class XC3, 30 mm cover, \( k = 0.6 \), \( \text{CO}_2 \) concentration in the air is 820 [mg/m\(^3\)], RH = 75 \% and reliability index \( \beta = 1.3 \). This analysis results in a value of service life which is approximately three times lower.

The resulting sustainability indicators assessed using Eq. (3) are shown in table 2; the resulting \( k_{SB} \) values indicate that the best choice from the point of view of sustainability is concrete A\(_1\). This is evidently influenced by the differences in service life.

### Table 1. Composition of mixtures

| Components [kg/m\(^3\)] | A\(_1\) | B\(_1\) |
|--------------------------|--------|--------|
| CEM I 42.5 R             | 346    | 133    |
| Ground granulated blast furnace slag | -      | 200    |
| Water                    | 173    | 150    |

### Table 2. Concrete properties and the final values of indicators \( k_{SB} \)

| Property                  | Concrete A\(_1\) | Concrete B\(_1\) | Concrete A\(_2\) | Concrete B\(_2\) | Concrete C\(_2\) | Concrete D\(_2\) |
|---------------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| 28-day cube strength [MPa] | 45               | 42.75            | 91               | 49.8             | 40.4             | 1.04             |
| Service life [years]      | 0.06             | 0.06             | 0.01             | 0.20             | 0.20             | 0.23             |
| Eco-costs [€]             | Normal           | Normal           | Normal           | Normal           | Normal           | Beta             |
| \( k_{SB} \)              | 1.04             | 0.45             | 0.23             | 0.22             |                  |                  |

(ii) To show the effectiveness of Eq. (3) in sustainability assessment as well as its ability to distinguish differences between concrete mixes (SCMs) exposed to frost. In this case the common service life in years is replaced by a value determined for the amount of scaling \( \rho_a \) per 100 freeze-thaw cycles. When calculating \( k_{SB} \) this “non-traditional” quantity reads \( L = 1/\rho_a \). Concrete mixtures A\(_2\) to D\(_2\) were analysed (adopted partially from [14]). Data from [28] were utilized for the frost effect. Table 4 lists the values of the resulting sustainability indicators and their statistical parameters.

### Table 3. Composition of mixtures

| Components [kg/m\(^3\)] | Concrete A\(_2\) | Concrete B\(_2\) | Concrete C\(_2\) | Concrete D\(_2\) |
|--------------------------|------------------|------------------|------------------|------------------|
| CEM I 42.5 R             | 389              | 301              | 301              | 301              |
| Aggregate 0–4 mm         | 812              | 812              | 812              | 812              |
| Aggregate 8–16 mm        | 910              | 910              | 910              | 910              |
| Zeolite Zeobau 200       | -                | 88               | 44               | 44               |
| Fine-ground blast furnace slag | -        | -                | 44               | -                |
| Fly ash                  | -                | -                | -                | 44               |
| Microground limestone    | -                | -                | -                | -                |
| Water                    | 140              | 168              | 161              | 164              |

The resulting \( k_{SB} \) values (see Table 4) indicate that in terms of durability the best choice from the four concretes attacked by frost is concrete A\(_2\).

Clearly, when the effect of other types of degradation and/or the effect of mechanical load on the service life are taken into account, the order of sustainability indicator values can change. This issue is at the focus of the authors’ ongoing research.
Table 4. Concrete properties and the final values of indicators $k_{SB}$

| Property                                      | Concrete A | Concrete B | Concrete C | Concrete D |
|-----------------------------------------------|------------|------------|------------|------------|
| Mean COV Pdf                                  |            |            |            |            |
| 90-day cube compressive strength [MPa]        | 63 0.06    | 58 0.06    | 67 0.06    | 56 0.06    |
| Scaling after 100 cycles [g/m²] [28]          | 120 - -    | 400 - -    | 560 - -    | 220 - -    |
| Eco-costs [€/m³]                              | 71 0.20    | 68.9 0.20  | 68.7 0.20  | 57.9 0.20  |
| $k_{SB}$                                      | 1.04 0.29  | 0.30 0.25  | 0.28 0.26  | 0.55 0.27  |

5. Conclusion
The paper presents a tool for sustainability assessment, which enables the quantification of sustainability and the comparison of concrete mixture variants in this respect, with an emphasis on durability and CO₂ emission. It can be employed when making decisions in the production of concrete to understand the required properties. It utilises the cradle-to-gate system boundary and the fully probabilistic approach, dealing with simple equations in which service life, performance and environmental impact (expressed as eco-costs) are used to determine a sustainability indicator as a sustainability quantification measure. A software tool designed for this purpose is briefly introduced. The last section discusses two simple illustrative examples, considering two degradation effects – concrete carbonation and freeze/thaw cycles. The authors believe the proposed methodology can serve as a supporting policy-making tool for the cement industry.

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