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## The assessment and prediction of concrete sustainability

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# The assessment and prediction of concrete sustainability

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**Abstract.** The sustainability of concrete and concrete structures is seeing increased attention; among other things, this is because 5% of global CO<sub>2</sub> emissions are produced by cement manufacturing. Responsible sustainability management requires effective tools for the quantification, i.e. measurement, or comparison of material, technological, and structural options. This is why there are a number of initiatives and approaches that aim to reduce global greenhouse gas emissions. Their project design uses techniques that assess whole structures and their usage; however, most of their input data is based on estimates. This paper presents a validation of a method of designing, assessing, and predicting sustainability for one material (concrete) with regard to its composition, relevant properties, and predicted value dispersion utilizing probabilistic approach.

## 1. Introduction

Sustainability is becoming one of the basic concepts in the design and operation of concrete structures throughout their life cycle, taking into account these three pillars: social, environmental and economic. In the construction sector sustainability is a rather complex issue, and all of these components must be considered from the very earliest stages of the existence of the structure in question – in other words, Life Cycle Assessment (LCA) procedures are being adopted. LCA is a method that evaluates the life cycle of a structure from the point of view of its impact on the environment. Consideration is generally given to energy and material costs, as well as to the environmental and social impact throughout the life cycle. In addition, the international document fib Model Code 2010 [1] discusses a performance-based design of concrete structures, listing three basic performance categories: usability (i.e. also service life), safety, and sustainability. Unfortunately, the any link between these quantities is not discussed.

In June 2016, the fib Technical Council approved the start of activities on The MC2020 project under the auspices of COM10: Model Codes, which initiated Task Group 10.1: Model Code 2020 to undertake the preparation of a single general code fully integrating the provisions for the design of new concrete structures with matters relating to the through-life management and care of existing concrete structures. MC2020 will take sustainability as a fundamental requirement, based upon a holistic treatment of societal needs and impacts, life-cycle cost, and environmental impacts [2].

## 2. Sustainability coefficients

This multi-criteria evaluation of buildings or large structures and the assessment of their sustainability are, as a rule, accompanied by many uncertainties which can devalue the results and their applicability. It might thus prove useful to focus attention on a simpler task first – the evaluation and comparison



of the sustainability of a material. To do this, the paper focuses on the quantification of sustainability related to the use of various types of concrete with regard to their durability, i.e. the resistance to degradation. Sustainability coefficients  $k_{SB}$  are determined using information about material performance, service life and eco-costs, as has been recently published [3], based on Building Material Sustainability Potential [4]. The aim of this paper is to show the possibility to approach future requirements and to simplify decision making as to the design and selection of concrete mixes in broader terms; i.e. not only with regard to load-bearing capacity or durability as is currently common. The procedure is further improved by using the probabilistic approach, i.e. by considering the input quantities as random quantities with a known probability distribution, with the output being values of statistical parameters  $k_{SB}$ , or the probability distribution of these quantities which can be also used when forming a sustainability limit state condition (as shown in [3]).

Sustainability can be quantified using normalized sustainability coefficients  $k_{SB}$  according to equation (1), where quantities  $L$  (service life),  $R$  (performance) and  $E$  (eco-cost) are divided by reference values  $L_{ref}$ ,  $R_{ref}$  and  $E_{ref}$  (arbitrary values hold always constant for the study in question), meaning that  $k_{SB}$  is then a dimensionless quantity whose value usually approximates 1.0.

$$k_{SB} = \frac{\frac{L}{L_{ref}} \cdot \frac{R}{R_{ref}}}{\frac{E}{E_{ref}}} \quad (1)$$

This formula can be effectively utilized for to compare sustainability coefficient values between members of a group of various concretes. All cases in a given group must always be considered to be situated at the same (or similar) location and to suffer the same type of degradation and/or loading. When evaluating sustainability, a suitable type of performance is considered and service life is determined with regard to the given/chosen type of degradation/loading.

Sustainability coefficients  $k_{SB}$  can also be analysed in a probabilistic mode simply by considering quantities  $L$ ,  $R$  and  $E$  to be random quantities and consequently the coefficient  $k_{SB}$  to be random as well. This might become more useful in the near future as sustainability-related issues become more frequent – see [2]. Moreover, a similar approach has been recently described in [5] with focus on a more complex task (unfortunately not fully applicable in engineering practice). Such an approach needs a definition of relevant sustainability limit state conditions; this is part of ongoing research. The present paper concentrates on statistical characteristics of  $k_{SB}$ , and presents an illustrative example, which is processed by the FReET-D software [6], supplemented by a function for  $k_{SB}$  analysis (FReET-SB option).

### 3. Example of the sustainability evaluation of various kinds of concrete

The Feasible Reliability Engineering Tool for Degradation effects assessment in reinforced and pre-stressed concrete structures (FReET-D) is used for probabilistic modelling of environmental degradation and can serve for design or performance-based specification. The FReET-D software is capable of predicting service life, performing statistical analysis (statistical parameters of degradation measures), sensitivity analysis (sensitivity of output on different inputs) and reliability analysis (assessment of reliability measures corresponding to target service life and different limit state functions) [6].

The composition of the mixture used in the three different concretes can be seen in table 1 (A – reference mixture, Portland cement only; B – with fly ash used as a substitute for a portion of Portland cement; C – with fine-ground slag). The strength of concrete is considered to indicate performance  $R$  in this example, and was gained by sample testing within the grant project GA ČR 103/07/0034 at Faculty of Civil Engineering, Brno University of Technology.

Table 2 shows the environmental impact values transformed into financial units. The concretes in question are supposed to suffer by carbonation, so the service life  $L$  is calculated as of the initiation period stage of reinforcement corrosion caused by concrete carbonation using an analytical model. The FReET-D tool with model Carb4b [7] are used. Basic input values were: concrete cover 30 mm; atmospheric  $CO_2$  concentration 820 [mg/m<sup>3</sup>]; RH = 70%; the  $k$ -value concept for concrete B  $k = 0.4$ ,

while  $k = 0.6$  for concrete C [8] in addition to data listed in table 1. Statistical parameters are shown in table 3.

The decisive values to be used in equation (1) and the resulting sustainability coefficient values are listed in table 3 including their statistical parameters. Note also that the values relevant to concrete A were used as reference, i.e.  $L_{\text{ref}} = L_A$ ,  $R_{\text{ref}} = R_A$  and  $E_{\text{ref}} = E_A$ .

**Table 1.** Composition of mixtures.

Components [kg/m <sup>3</sup> ]	Concrete A	Concrete B	Concrete C
CEM I 42.5 R	389	290	290
Aggregate 0/4 mm	812	812	812
Aggregate 8/16 mm	910	910	910
Fine-ground blast furnace slag (3800 m <sup>2</sup> /kg)	-	-	194
Fly ash from Dětmarovice	-	194	-
Water	161	182	160

**Table 2.** Eco-costs.

Components	Concrete A	Concrete B	Concrete C	Ref.
CEM I 42.5 R (0,109 € /t) [€]	42.4	31.6	31.6	[9]
Slag (0.069 € /t) [€]	-	-	13.4	[10]
Fly ash (0.060 € /t) [€]	-	11.6	-	[10]
Aggregate (0.007 € /t) [€]	12.1	12.1	12.1	[10]
Total eco-costs in € / m <sup>3</sup> of concrete	54.5	54.3	57.1	

**Table 3.** Concrete properties and the final values of coefficients  $k_{SB}$ .

Property	Concrete A			Concrete B			Concrete C		
	Mean	COV	Pdf	Mean	COV	Pdf	Mean	COV	Pdf
60-day cube strength [MPa]	71.9	0.06	Normal	47.2	0.06	Normal	70.5	0.06	Normal
Service life [years]	125	0.17	Normal	73	0.16	Normal	151	0.26	Normal
Eco-costs [€]	54.5	0.20	Rectangular	54.3	0.20	Rectangular	57.1	0.20	Rectangular
$k_{SB}$	1.04	0.28	Beta	0.40	0.27	Beta	1.18	0.33	Gamma

The resulting  $k_{SB}$  values (see table 3) show that the best choice in terms of sustainability is concrete C in spite of having higher eco-costs than variants A and B – this is clearly influenced by the fact that concrete C has the longest service life due to the content of granulated slag (considering concrete carbonation). Evidently, when the effect of other degradation types and/or the effect of mechanical load on the service life [11] are taken into account, the order of sustainability coefficient values can change. This factor is at the focus of the authors' ongoing research.

#### 4. Conclusion

This paper can be viewed as a continuation of previous articles written by the authors, where they made attempts to utilize the sustainability coefficient to describe concrete sustainability in a deterministic approach. A full probabilistic approach is described briefly for sustainability indicator analysis together with the probabilistic modelling of degradation phenomena (due to environmental processes and used to predict the service life). To illustrate such approach, an example of three different concrete mixtures (with different additions) was studied and implications for sustainability were drawn. The presented methodology can be used for a wide range of applications, considering various degradation effects or their combinations; the authors will continue presenting the results of this as part of ongoing research. The authors believe this might become more useful in the near future as issues of sustainability enter into the centre of attention due to the current international progress being made on the new fib Model Code 2020.

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