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Sustainability assessment of concrete mixes

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Abstract. Since concrete is one of the most important and useful materials in the construction sector, which, unfortunately, has an adverse impact on the environment, it is evident that correct procedures for designing and/or assessing concrete structures need to be created. Model Code 2020 with the focus to sustainability stated to be one of main aspiration goals, which will have implications for subsidiary performance requirements critical to structural design, integrate life cycle perspective, reliability and performance based concepts and end-of-service-life issues. Evidently the combined impact of the service life and relevant safety level of structures on the economical and environmental aspects desire full consideration of engineers and stakeholders. Consideration is also given to energy and raw material costs, as well as to environmental impact throughout the life cycle – e.g. due to emissions.

1. Introduction

The concept of sustainable development and related governance principles and rules are becoming increasingly popular worldwide. The intensive debate on sustainability issues in the construction industry has led to the development and implementation of various systems for defining and assessing the sustainability of buildings around the world. Today worldwide buildings are estimated to account for 50 % of all energy consumption, and more than 50 % of global emissions [1], as well as consuming between 30 and 40 % of the global electric energy [2]. Environmental pollution, deforestation, soil erosion, ozone depletion, fossil fuel depletion, and human health risks are the significant consequences of design, construction and operation of buildings, which disregard the impacts on the environment.

The development of our society places greater stress on the reduction of energy demands in all areas of life. The European Union has vowed to reduce greenhouse gas emissions by 40% by 2030 compared to 1990 levels and to increase the share of renewable energy to at least 27%. The aim of the energy plan for 2050 is to additionally reduce greenhouse gas emissions by more than 80% when compared to 1990 [3]. The EU has committed itself not only to reducing greenhouse gas emissions, but also to the 17 goals of sustainable development (Sustainable Development Goals). The Sustainable Development Goals are the result of a three-year long negotiations that began at the 2012 UN Conference on Sustainable Development in Rio de Janeiro. The agenda for sustainable development was formally adopted by the UN Summit on 25 September 2015 in New York with the document Transforming Our World: The 2030 Agenda for Sustainable Development (Figure 1). The new global goals are based on the knowledge that challenges such as eradication of poverty, reduction of discrimination, protection of the planet, strengthening freedom and security are mutually interconnected [4, 5]. At first sight, the described goals address separate areas, however, these areas are very closely connected. There are further 169 subsequent targets in total that are part of the individual goals.

Figure 1. Sustainable Development Goals [4].

The last goal of the economic pillar (Goal 12) is to ensure sustainable consumption and production. The goal relates to the implementation of a ten-year framework of programmes on sustainable consumption and production involving all countries. It assumes cooperation of developed and developing countries in sharing practical experience, technologies and innovations to achieve sustainability in production, including a reduction of waste production and use of less environmentally harmful products in production. Goals 13-15 on the other hand deal with the environment. The goals focus on global climate changes and react on the dangers associated with them and with natural disasters. According to the document, it is crucial that countries incorporate the protection of the environment into their national policies, increase their participation in financing global measures against climate change, and intensively participate in education and raising the awareness of climate changes. Authorities involved in the development of the goals included all UN member countries, representatives of civil society, the private sector and academic communities. The document, unlike previous strategies, is considered to be the most ambitious instrument of global community since it can be applied universally to all countries, defines much higher targets and expects a systemic change in the current functioning of the world community. The Agenda 2030 and its 17 goals form the central focus of the functioning of the UN and all related mechanisms [1]. All these aspects also lead to the sustainability of concrete structures.

2. Concrete sustainability assessment

Cities and buildings have recently become the central point of interest. In spite of being the key “engine” of social and economic growth, cities have not managed to address emerging problems and existing challenges such as city growth, congestion, air pollution, poverty, greenhouse gas emissions and others. The aim of sustainable development is to design buildings and cities that meet the user requirements in regard to functionality and comfort, which exhibit a certain degree of aesthetic and customer design quality, and which contribute to decreasing of consumed resource and of the adverse impacts on local and regional environments. Sustainability approach is a key conceptual principle in a many activities. Namely design, production, construction, operation, maintenance, repair and demolition of building or any civil engineering work forming the built environment. 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 CO_2 emissions. Therefore, implementation of sustainability criteria into performance-based design and assessment is needed and it is in recent years in the centre of research agenda all around the world. Particularly the activities of fib Commission 7 Sustainability and fib Commission 10 are working on the new Model Code 2020 with the focus to sustainability stated to be one of main aspiration goals, which will have implications for subsidiary performance requirements critical to structural design, integrate life cycle perspective, reliability and performance based concepts and end-of-service-life issues [6, 7]. In previous period this issue has been addressed e.g. in [8] and [9] in a certain way.

Evidently the combined impact of the service life and relevant safety level of structures on the economical and environmental aspects desire full consideration of engineers and stakeholders [10]. 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 [11, 12], 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 k_{SB} which enables quantification. A quintessential question for the implementation of the principles of sustainable development is whether to treat social, economic and environmental issues equally or whether the protection of the environment is more important and therefore should dominate the other issues. Despite the increasingly frequent debates on the "weight" of the individual pillars, all three pillars are now considered to be important in the context of sustainable development and must all be taken into account.

$$BMSP = \frac{performance \times service\ life}{environmental\ impact} = \frac{R \times L}{E} \tag{1}$$

Material sustainability can be quantified for practical purposes using all the material aspects together by normalized Eq. (1), 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.

$$k_{SB} = \frac{\frac{R}{R_{ref}} . \frac{L}{L_{ref}}}{\frac{E}{E_{ref}}} \tag{2}$$

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. In this equation (2), "performance" R means for instance the load-bearing capacity, deformability, resistance to degradation or other properties of the material or structure expressed in corresponding units. The service life L is usually given in years; its definition is described in the "Service life" section. Quantity E (the "impact on the environment") is usually described as a string (sum) of data including, e.g. bound emissions of various kinds, energy consumption, wear and tear, etc. It is clear that these can be quantities that are expressed using various different units which thus need to be converted into common units so as to enable the combination of all impacts into one value, E. These common units are usually financial, and discussions concern eco-costs which, according to e.g. [13], represent the costs of measures taken to reduce environmental impact to a sustainable level, or global warming potencional (GWP). Eq. (2) can be further enhanced by considering costs, C of concrete (material and production) leading to a modified indicator, $k_{SB,\ C}$. However, it should be noted that cost of materials are mostly region or country dependent. There is also what is called a probabilistic approach with each quantity in equation (2) i.e. by considering the input quantities as random quantities with a known probability distribution, with the output being values of statistical parameters kSB, or the probability distribution of these quantities which can be also used when forming a sustainability limit state condition (as shown in [17]). The relationship of equations (1) and (2) is shown in Figure 2.

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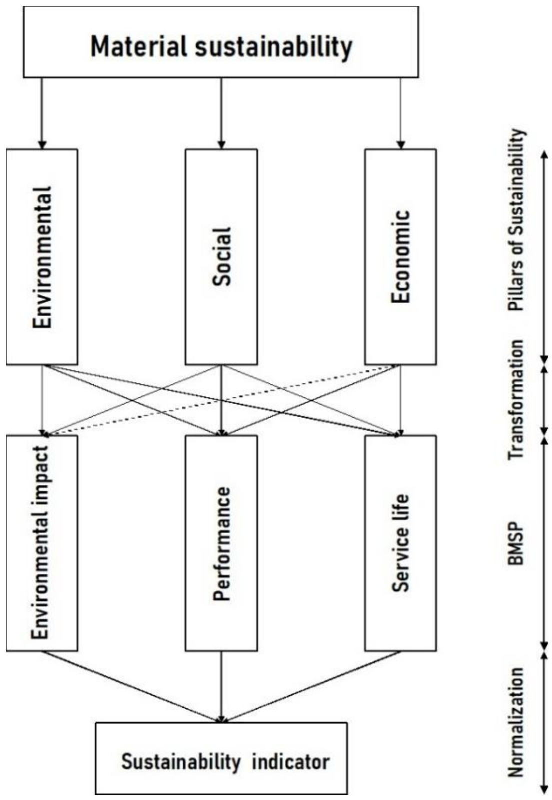

Figure 2. Graphical representation of BMSP transformation to indicator $k_{SB.}$

2.1. Example of the sustainability evaluation of various kinds of concrete

As an exam, five various type of concrete mixtures. Composition of concrete mixtures see Table 1. These mixtures for concrete fabrication were designed for experimental testing and numerical analysis as presented in articles [14, 15]. Limestone coarse aggregate gravel and silica sand were used. Mixtures contained Type II-V cement (TII-V), Class C fly ash (C) and Class F fly ash (F). Mixtures were marked in the following tables according to cementitious materials and their percentage replacement, e.g. 80TII-V/20F stands for 80 % Type II-V Cement, 20% Class F fly ash.

Table 1. The composition of concrete mixtures [kg/m^3].

Mix ID	***Water content***	***Cement TII/V***	***Class C Fly Ash***	***Class F Fly Ash***	***Coarse Aggregate - Gravel***	***Fine Aggregate - Natural Sand***
100TII-V	147	335	-	-	1073	709
80TII-V/20F	147	2678	-	67	1073	689
60TII-V/20C/20F	147	201	67	67	1073	668
60TII-V/30C/10F	147	201	100	34	1073	668
60TII-V/30F/10C	147	201	34	100	1073	668

All mixtures contained 335 kg/m^3 of cementitious material and the water/cementitious materials ratio was chosen as 0.44. Concrete strength and diffusion coefficient are both time dependent parameters and they can significantly influence the sustainability indicator value. Basic information about the diffusion coefficient and the compressive strengths at 28 days from laboratory experiments [14, 15] were investigated and are shown in Table 2. Sustainability indicators k_{SB} have been analyzed with the use of Eq. (2); relevant values of material parameters are shown in Table 2. In this analysis for the material performance, R stands the compressive strength, for service life, the inverse value of diffusion coefficient, for environmental impact, E eco-costs analyzed by [13] and E footprined analysed by [13,16] were employed. In Eq. (2) applied values of reference values were chosen corresponding to control reference mixture of 100% Portland cement (100TII-V). The resulting sustainability indicator for individual concrete mixture are shown in Table 2.

Table 2. Diffusion coefficient, compressive strength, eco-cost, carbon-footprint.

Mix ID	Eco-costs [€/m^3]	Dc (28 days) [m^2/s]	Strength (28 days) [Mpa]	Carbon footprint [CO_2/t]	$k_{SB\ (eco\text{-}costs)}$	$k_{SB\ (carbon\text{-}footprint)}$
100TII-V	51.66	5.590E^{-12}	28.00	271.25	1.00	1.00
80TII-V/20F	48.49	5.380E^{-12}	28.10	248.94	1.11	1.14
60TII-V/20C/20F	44.64	6.310E^{-12}	29.20	226.48	1.07	1.11
60TII-V/30C/10F	44.31	5.110E^{-12}	32.40	226.41	1.48	1.52
60TII-V/30F/10C	44.98	4.800E^{-12}	30.00	226.55	1.43	1.49

As highlighted in Table 2, the mixture 60TII-V/30C/10F appears to be the most "sustainable", followed by concrete 60TII-V/30F/10C. Every concrete mixtures performed better than the control mixture of 100% Portlad cement (100TII-V). 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.

3. Conclusions

The present paper concentrates on the sustainability analysis of concrete based on the material level. 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 deterministic method. The contribution presents a tool for the management of sustainability which enables its quantification and the comparison of mixture variants for the production of concrete with certain properties, and with an emphasis on durability issues. Simple relations in which service life, performance and eco-costs appear are presented for sustainability coefficients. The example shows the sustainability assessment of five various concrete mixtures. Of all mixtures, the mixture 60TII-V/30C/10F appears to be the most "sustainable".

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