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Assessment of the sustainability potential of concrete and concrete structures considering their environmental impact, performance and lifetime

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HIGHLIGHTS

- Sustainability potential influenced by environmental impact, service lifetime and performance.
- Improved environmental impact with reduced cement content.
- Cement usage efficiency increases with concrete strength.
- UHPC provides high sustainability potential.

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ABSTRACT

Sustainable structural engineering is based on the basic principle that the energy and resources consumption due to the construction and operation of a structure must be minimized. Relating to concrete structures this principle can be realized by the use of the material in the most efficient way considering its strength and durability within the service life of the structure. On this background this paper outlines the three basic possibilities to increase the sustainability of a structure, i.e. methods to assess and reduce the environmental impact of concrete, means to increase the performance of concrete and design concepts which increase the possible lifetime of a concrete structure. The presented concept is applied to the concretes with the greatest potential in sustainability, i.e. green concretes as well as ultra high performance concretes. Thereby, the basic principles of mix design of green concrete are introduced and a systematic study of the influence of the cement content of these concretes on the fresh and hardened concrete properties is presented. With regard to UHPC, the sustainability potential of this concrete type is analyzed within a literature review. From the results it can be seen, that green concretes possess a very high sustainability as long as they do not underlie any durability requirements. The sustainability of green concrete subjected to corrosive exposures such as carbonation or frost, however, still has to be proven. UHPC, on the other hand, does not underly this constraint, as it provides superior mechanical and durability performance compared to the environmental impact resulting from concrete production.

1. Introduction

More than any other industry, the building industry is affected by the ongoing sustainability debate. Primarily, this is due to the pronounced environmental impact going along with the production of building materials, the erection of buildings and structures and the subsequent use of these structures [1,2]. This is especially true for structures made out of concrete, as the production of this material – and here especially the production of its raw material cement – is highly energy intensive and prone to large emissions of CO_2 [3]. Reducing the environmental impact during concrete production without looking at the impact on the performance and durability of the material however would fall short, as the required lifetime of concrete structures normally ranges between 50 and 100 years and thus normalizes the environmental impact over a long time span. Increasing the sustainability of building structures therefore requires both a reduction of the environmental impact going along with the erection, maintenance and operation processes as well as an increase of the durability of the structure at maximum technical performance. This relation is detailed in Eq. (1).

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$$\text{Building material sustainability potential} \sim \frac{\text{Lifetime performance}}{\text{Environmental impact}} \qquad (1)$$

Even though the definition given above differs from standard definitions of the term sustainability, it is well in line with the later, as it addresses the three basic pillars of sustainability – i.e. environmental aspects (by introducing the environmental impact), social and economical aspects (hidden in the lifetime and the performance parameters). As social and economical aspects however are extremely difficult or even impossible to evaluate during the concrete development process (i.e. the mix design), the definition given in Eq. (1) provides the engineer with a simple way to quantify the advantages and disadvantages of a certain concrete type with regards to its potential as a sustainable material. Whether this potential is used later on in the design and construction process is up to the designer of the building or structure.

According to Eq. (1), there are three basic approaches to achieve a sustainable use of concrete: (1) the optimization of the composition of the concrete in view of its environmental impact while maintaining an equal or better performance and lifetime; (2) the improvement of the concretes performance at equal environmental impact and lifetime; (3) the optimization of the lifetime of the building material and the building structures at equal environmental impact and performance. This paper deals with the combination of the aforementioned approaches (1)–(3) and primarily outlines the procedures applied during this optimization process. In the following this combination of both life cycle assessment techniques (often called eco balance) and service life design techniques is defined as assessment of sustainability potential.

In a first step, the principal methods for evaluating the environmental impact of concrete production is shortly summarized in this paper (see Section 2). Building up on that, in Section 3, the mix design procedure of concretes with extremely low cement contents as well as of concretes with ultra high performance is presented. Both types of concretes possess a very high potential in increasing the sustainability of concrete structures. From Eq. (1), however, it is clear, that all changes in environmental impact and performance must be evaluated regarding possible changes in the lifetime of the concrete or the concrete structure. Therefore, a service life design must be carried out in order to optimize the concrete composition and execution (e.g. the concrete cover) in view of the designed lifetime of the structure. Within this design process, both the performance of the concrete as well as the various loadings acting simultaneously on the concrete must be considered (see Section 4). As a matter of principle, all efforts will however only guarantee a maximum in sustainability unless both the lifetime and the performance are fully utilized by the user of the structure. As the actual lifetime by definition cannot be calculated, the service life of the material, component or structure can only be considered as auxiliary parameter in this calculation.

2. Evaluation of the environmental impact of concrete using the eco-balance method

The starting point in optimizing the sustainability potential of building materials and structures lies in determining the environmental impact in a standardized manner within a so-called eco-balance as described e.g. in the European standards EN ISO 14040 and EN ISO 14044 [4,5]. The impact of every substance emitted into the environment hereby can be attributed to one out of 7 impact categories, which have been internationally agreed upon (see Table 1).

Table 1
Impact categories classifying the environmental impact of industrial processes [4,5].

Category	Designation	Unit
CED-fossil	Cumulative Energy Demand (non-renewable)	Joule
CED-renewable	Cumulative Energy Demand (renewable)	Joule
GWP	Global Warming Potential	kg CO_2-equivalent
ODP	Ozone Depletion Potential	kg R11-equivalent
AP	Acidification Potential	kg SO_2-equivalent
NP	Nutrification Potential	kg PO_4-equivalent
POCP	Photochemical Ozone Creation Potential	kg C_2H_4-equivalent

The environmental impact resulting from the production of 1 m^3 of concrete can be calculated by multiplying the impact resulting from the production of each raw material with the amount of raw material used in the concrete and by summing up the individual impacts. Table 2 gives an overview on the environmental impact of typical concrete raw materials. In many countries exact data on specific raw materials can be obtained from the raw materials producer using so-called environmental product declarations (EPD, [6]).

As can be seen from Table 2, cement has a very decisive influence on the environmental impact of concrete, taking into account the large amounts of cement needed in the production of a standard concrete. The replacement of cement by reactive additives such as fly ash or finely grounded slag sand however is only beneficial to the environment, as long as these materials are treated as industrial wastes and are therefore not attributed to the eco-balance of the concrete (see Table 2). Respect must also be given to the sometimes limited availability of these materials [11,12], which has led to a worldwide search for new hydraulic binders with reduced environmental impact but unlimited availability. Examples for this development are Celitement [13] and calcined clays [14].

3. Mix development of concretes with low environmental impact and high performance

3.1. Concrete with minimum environmental impact – green concrete

Besides the search for binders with reduced environmental impact a very promising approach in designing concretes with minimum environmental impact lies in reducing the amount of binder in the production of concrete. Great progress with regard to this approach could be achieved in Denmark in the last decade. Glavind et al. [15,16] for example presented concretes with mean compressive strengths around 30 MPa in which cement was systematically replaced by reactive additives such as fly ash or slag sand as well as stone powders. Proske and Graubner et al. [17] report about the development of low strength concretes, where Portland cement was successfully replaced by limestone powder, fly ash and composite cements and by which the environmental impact of the concrete was significantly lowered while maintaining sufficient strength and durability. These findings were confirmed by own results of the authors presented in [18]. A systematic investigation on the mix design principles of ecological concretes – i.e. concretes with a strongly reduced cement clinker content – was presented by Fennis [19]. By using packing algorithms such as the Compressible Interaction Packing Model (CIPM) Fennis was able to significantly reduce the amount of cement clinker needed for the production of concrete. With regard not only to the building material but also to the building structure fib bulletins 28 and 67 [20,76] give a good overview on the state of the art in sustainable building design.

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