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Eco-friendly concretes with reduced water and cement content – Mix design principles and application in practice

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HIGHLIGHTS

- Principles for the development of eco-friendly concretes.
- Concrete mixes with low cement and water content (C < 180 kg/m^3).
- Efficient use of SCMs (fly Ash, GGBS) and limestone powder.
- Investigation of concrete properties.
- Practical application.

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ABSTRACT

The major environmental impact of concrete is caused by the CO_2-emission during the cement production. Great potential for the reduction of the impact is seen especially for concretes with normal strength. The use of superplasticizer and high reactive cements as well as the optimization of the particle size distribution and the reduction of the water content allows a significant reduction of the Portland cement clinker in the concrete. Essential is the addition of mineral fillers (e.g. limestone powder) to provide an optimal paste volume. In addition the already practicable substitution of the cement clinker by secondary raw materials like fly-ash or furnace-slag is an appropriate opportunity but limited by the availability of these resources.

In several test series the fresh and hardened concrete properties of water and cement reduced concretes were investigated, especially the workability, the strength development, the design relevant mechanical properties as well as durability aspects like carbonation. It was shown that concretes with cement contents lower than 125 kg/m^3 were able to meet the usual required workability, strength (app. 40 MPa) and mechanical properties. The carbonation depth of concretes with 150–175 kg/m^3 of cement was equal or lower than the depth of the conventional reference concretes for exterior structures. The ecological advantages were identified, using the environmental performance evaluation. A reduction up to 50% in environmental impact compared with the conventional concrete and a reduction of more than 65% by using blast furnace cement was calculated. The application in practice was verified conducting full-scale tests in a precast and ready-mix concrete plant. The special requirements on workability and early strength were fulfilled with a cement content of 150 kg/m^3.

1. Introduction

To ensure the competitiveness of concrete as a building material in the future, it is essential to improve the sustainability of concrete structures. Great potential for the reduction of the environmental impact and the consumption of scarce resources has been identified in the field of concrete construction, especially in the production of raw materials, concrete technology and structures [1] (see Fig. 1). For concretes which are developed, produced and used in an environmentally friendly manner the term “Green Concrete” [2] is commonly used.

The major environmental impact of concrete comes from the CO_2-emissions during cement production as a result of the calcination and grinding process. The CO_2-emissions are mainly related to the decarbonation of the limestone, the fuel consumption and the electricity consumption [3]. Approximately five percent of the global anthropogenic CO_2-emission is connected with the production of 3.3 billion tons of cement per year (2010) [4]. Therefore, the reduction of the cement–clinker content has positive effects on the environmental life cycle assessment of the concrete and can be achieved by the optimization of the mixture design [5,12]. Some

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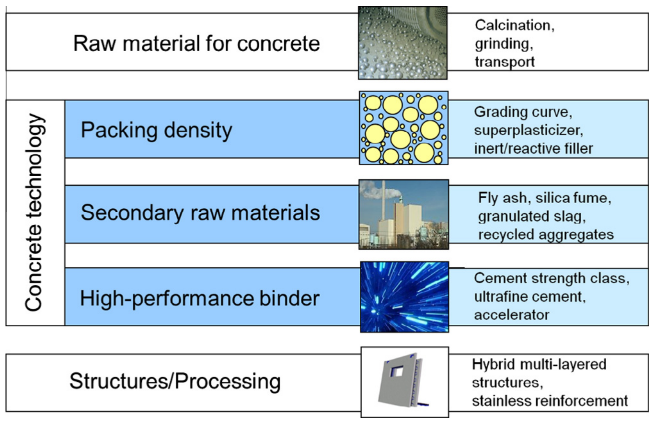

Fig. 1. Opportunities for ecological optimization in concrete construction [1].

research works are already carried out to reduce the Portland cement content in the concrete [1,2,5–11].

This paper presents the general procedure for the development of structural concrete with low environmental impact and normal compressive strength. This includes the stepwise development of the mix design. The results of performance tests on cement reduced concretes conducted in laboratory conditions are also presented. In addition, the advantages regarding to the environmental performance evaluation were verified. Finally, the application in the precast industry as well as the technical advantages of the cement reduced green concretes is presented.

Compared to other studies in the field of eco-friendly concretes, the focus of the research is the efficient use of the Portland cement clinker and other reactive materials by the reduction of the water content in concrete. Furthermore, the suitability of grinded limestone which is available worldwide in a sufficient scale is analyzed in this context.

2. Principles for the development of low carbon concrete

Based on experimental results, a stepwise procedure for the development of low carbon concretes was developed. Following principle steps are recommended:

(1) Selection of cement with high strength class and eco-friendly constituents.
(2) Minimization of the water content and the cementitious material in the paste of the concrete.
(3) Optimization of the paste volume.

The first step is the selection of the cement. The environmental impact of the cement should be as low as possible and at the same time the strength performance relatively high. Composite and slag cements (CEM II and CEM III) with strength class 42.5 and 52.5 as well as Portland cement (CEM I) with strength class 52.5 are appropriate. However, the increased use of slag and slag cements as well as fly ash is limited in several countries by the availability of these materials and the requirements for the early strength of concrete. For future application, along with modified low-water-concrete technology, the development of environmental friendly cements with higher limestone content is planned.

In the second step the volume of the cement and cementitious materials should be minimized. To achieve a significant reduction, the concrete technology for ordinary concretes was modified based on the principles of high performance concretes. Fig. 2 shows that the application of high performance superplasticizers increases the dispersion and actual packing density of the solid powder particles (<0.125 mm). The optimization of the particle size distribution also leads to a lower required water volume and a lower permeability. This allows the reduction of the water/powder-ratio in the mixture, still providing sufficient workability. Based on the decreased water content, along with an increase in strength and durability, the reduction of the cement content is possible. The corresponding cement and water volume is substituted by environmentally friendly powders like limestone, fly ash or slag. Considering the availability of the reactive materials, inert materials like limestone should be preferred. However, investigations have shown a considerable contribution of optimized limestone powders to the strength development.

It has to be considered, that a certain paste volume is necessary to maintain the required workability. This implies that a minimization of the paste content and hence an additional reduction of the cement content is possible through an optimization of the aggregate packing (Step 3).

The principles of the concrete development and the effects on the concrete strength, the water content and the workability are also presented qualitatively in Fig. 3. The reduction of the clinker increases with the decrease of water and the contribution of cement and additives on the performance.

For the practical application of green concretes, questions must be answered regarding to their workability, pumpability, strength development and durability. Changes in the conventional mixtures and evolution into eco-friendly concrete must not diminish the material performance. For instance, when cement reduced concretes are to be used for exterior structures, the durability, including the performance against carbonation induced corrosion is of great importance [13].

3. Laboratory tests

3.1. Overview and targets

At the Technische Universität Darmstadt, intensive studies on the topic of "Green Concrete" were conducted as part of research projects in the field of sustainable concrete structures. Different kinds of concretes with reduced cement content were developed especially for reinforced concrete structures. The initial investigations based on laboratory tests are described below.

A compressive strength of 10 N/mm^2 at an age of 24 h without heat treatment was targeted to enable the demolding. After 28 days a compressive strength of 38 N/mm^2 was desired to obtain compressive strength class C25/30. The cement reduced concretes must have sufficient workability and concrete surface without many air voids. Therefore the slump flow value according to DIN EN 12350-05:2009-08 was chosen to be near 550 mm. The cement

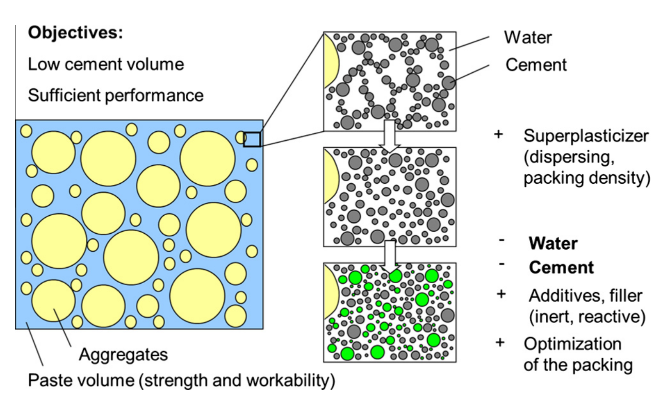

Fig. 2. Evolution from the traditional mixture proportion to cement reduced green concrete [5].