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Review

Critical review on eco-efficient ultra high performance concrete enhanced with nano-materials

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ABSTRACT

Ultra high performance concrete (UHPC) is an innovative high-tech material, designed for the future. However, the high dosage of both Portland cement and silica fume, not only increases the cost of UHPC, but also represents a significant drawback regarding sustainability. This paper combines a critical review on UHPC mixture design methods with a discussion on the use of nano-materials in the latter aiming at reaching an eco-efficient UHPC. Based on a comprehensive bibliographic survey and a crossed analysis on both topics, conclusions are drawn towards sustainability of UHPC.

Contents

1. Introduction

Nowadays, the sustainability of the construction sector must be a priority for the scientific community. In this scope, the development of innovative materials and methods aiming at extending the life-time of both existing and new structures is mandatory.

Generally, two fundamental approaches have been developed to improve the mechanical performance of ordinary concrete: densified with small particles (DSP) and macro defect-free (MDF). Bache et al. [1] presented the concept of DSP in the 1980s which consists in developing a concrete with a dense granular matrix. Birchall et al. [2] developed the MDF concept to improve both the ductility and the mechanical properties of ordinary concrete. The latter consists of polymer-modified mortars, known as MDF concretes, requiring a particular production process, such as polymerization, which fills concrete pores, thus leading to extremely compact and high strength matrices. Although increasing the compressive strength, both approaches reduce ductility, since the latter varies inversely with the former.

Typically, MDF mixtures are highly viscous and therefore their workability decreases by adding fibers, being this fact the main shortcoming of this approach. For this reason, efforts have been

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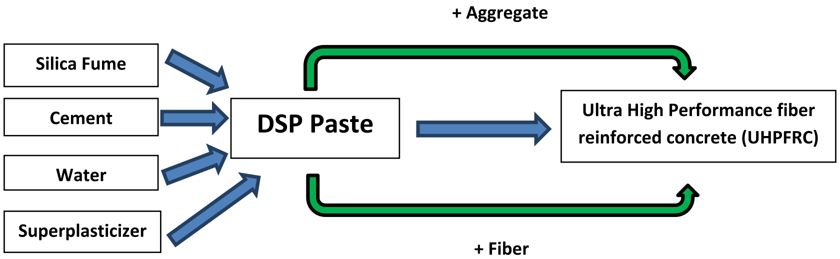

Fig. 1. Typical types of DSP approaches.

focused in adding fibers to DSP mixtures, which finally resulted in the development of ultra high performance fiber reinforced concrete (UHPFRC) [3] or simply ultra high performance concrete (UHPC). The mechanism of this approach is shown in Fig. 1. This innovative high-tech material is thus characterized by a dense microstructure, which presents ultra high compressive strength, higher than 150 MPa, and ultra high durability [4–6]. The enhanced mechanical properties and durability of UHPC has been widely reported [7,8], as well as several structural applications for the latter, particularly rehabilitation of concrete structures [9–12]. However the high dosage of Portland cement and silica fume (SF) in the main composition of UHPC, not only increases its cost, but also presents drawbacks regarding sustainability [13,14]. Taking into account both the enhanced mechanical properties of UHPC and its high environmental impact, it seems worthwhile to investigate a way to produce UHPC with low Portland cement content.

Mehta [15] has recommended three means for concrete industry to reach sustainability: (1) to consume less concrete by developing innovative architectural and structural designs for both erection of new construction and rehabilitation of existing structures, (2) to reduce the Portland cement dosage in concrete mixtures by using a smart proportioning approach, and (3) to reduce the Portland cement dosage in concrete mixtures by using a higher volume of one or more supplementary cementitious materials.

From the possibilities above-mentioned, the last two have to do with concrete mixture design. In the light of the second one, several mix design methods have been developed to optimize the mixture proportion of UHPC. These have been developed based on different principles, which makes it difficult to compare the effectiveness of each one and the properties of the resulting UHPC. For this reason, the first part of the study herein presented reviews the design methods that have been developed so far for UHPC mixtures, and discusses their procedures, advantages and drawbacks.

Regarding the third alternative, the use of micro and nano-sized supplementary cementitious materials (SCMs) has been widely studied to partially replace Portland cement in UHPC. The use of SCMs in UHPC mixtures is therefore discussed in the second part of the present study. The main goal of the present paper is to review most relevant developments regarding the two approaches referred to and thus to provide valuable scientific information and guidelines for the selection of an appropriate mixture design method aiming at achieving an eco-efficient UHPC, i.e. a new material combining the exceptional mechanical behavior of UHPC but with sustainability requirements.

2. Mix design methods for UHPC

UHPC results from the mixture of several constituents giving rise to a highly complex material in hardened state. The higher number of constituents in relation to conventional concrete, together with a higher number of possible combinations and relative proportioning, makes the behavior of this type of concrete more difficult to predict. In recent years, several studies (described next) have been conducted aiming at optimizing the mixture proportion of UHPC.

De Larrad et al. [16] developed the Linear Packing Density Model (LPDM), according to which the interaction between different size classes of constituents are described by functions. LPDM was found to be efficient in predicting optimal proportions for both cement paste and concrete. However, due to its linear nature, this model was not able to address the relationship between packing density and proportions of materials. The Solid Suspension Model (SSM), based on the virtual packing density concept, was then introduced to improve LPDM. This new model allowed producing a fluid mortar with a 0.14 water-binder ratio and a compressive strength of 236 MPa with a 4-day curing at 90 °C [16].

Later on, De Larrad et al. [17] introduced the compressible packing model (CPM), the third generation of packing models. The model was based on both the virtual packing density and the compaction index concepts. The former is, by definition, the maximum packing value, which is reachable by optimizing the positioning of grains, without altering their shape. Two interaction effects must be accounted for in this calculation: the wall effect, applied by coarser grains, and the loosening effect, exerted by the finer particles. In this model, it is assumed that those interactions are additive, which means that a possible intersection between disturbed zones is neglected [18].

Richard et al. [7] developed two products of reactive powder concrete (RPC), namely RPC 200 and RPC 800 by optimizing the granular mixture using CPM. RPC 200 uses a combination of fine quartz, siliceous sand, SF and Portland cement to form a cementitious matrix supporting straight smooth steel fiber reinforcements. These steel fibers are generally 13 mm long and have a diameter of 0.15 mm. RPC 800 mixture composition is similar to RPC 200 but steel fibers are replaced by stainless steel microfibers, less than 3 mm long. Curing condition is 250–400 °C with 50 MPa compacting pressure during casting of the concrete [7].

Geisenhanslüke et al. [19] presented a packing procedure for mixture proportioning of UHPC to be produced with locally available materials. The developed model covered all the necessary variables of both the mixture and the raw materials, such as particle size distribution, particle shape, and particle density. It is reported that, by using multi-grained fines, the dosage of Portland cement can be reduced, whereas workability, strength and durability of ordinary concrete, high performance concrete and UHPC are increased.

Fennis et al. [20] developed an ecological UHPC with low cement content by using particle packing technology in concrete mixture design. These authors stated that with the adopted approach the cement content is reduced more than 50% and the corresponding emissions of CO_2 are reduced by 25%.

Lohaus et al. [21] presented the superplasticizer-based water demand (SWD) approach to obtain a robust mixture proportion of UHPC. This model describes the achievable consistency of paste using superplasticizers as a function of the water-to-powder ratio.