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Review

A review on ultra high performance concrete: Part I. Raw materials and mixture design

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HIGHLIGHTS

- Four theoretical principles for production of UHPC, including reduction in porosity, improvement in microstructure, enhancement in homogeneity, and increase in toughness, are reviewed.
- Effects of different raw materials on performance of UHPC are summarized.
- Mixture design, sample preparation, and curing regimes are discussed.
- Use of conventional materials and common technology are trends for production of UHPC.

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ABSTRACT

Ultra high performance concrete (UHPC) refers to cement-based materials exhibiting compressive strength higher than 150 MPa, high ductility, and excellent durability. This paper reviews the theoretical principles, raw materials, mixture design methods, and preparation techniques for UHPC. Reduction in porosity, improvement in microstructure, enhancement in homogeneity, and increase in toughness are four basic principles for UHPC design. Raw materials, preparation technique, and curing regimes have significant influence on properties of UHPC. The use of widely available supplementary cementitious materials, such as fly ash and slag for partial/complete replacement of cement and silica fume, could significantly reduce the materials cost without sacrifice of strength. The use of high temperature curing results in denser microstructure and better performance than room temperature curing does, but obviously limits its applications of UHPC. Thus, preparation of UHPC using widely available raw materials, common technology, such as conventional casting and room temperature curing, are trends for production of UHPC.

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1. Introduction

During the past four decades, researchers all over the world have been attempted to develop high performance cement-based materials, which include hot-pressed cement, macro-defect-free cement (MDF) [1], densified with small particles (DSP) [2] and slurry infiltrated fiber concrete (SIFC) [3], etc. Although these materials have excellent performance, they can hardly be used in practice because of complicated forming process and high costs [1–4]. In 1993, Richard et al. [5,6] used components with increased fineness and reactivity to develop reactive powder concrete (RPC) via thermal treatment. RPC was characterized by high binder content, very low water-to-cement ratio (w/c), use of silica fume, fine quartz powder and superplasticizer and fibers [7]. It generally has high mechanical properties (compressive strength over 150 MPa) and ductility [8]. Furthermore, it exhibited high toughness and excellent durability [9]. In the following year, De Larrard [10] introduced the term "ultra high performance concrete" (UHPC). The production of UHPC often uses thermal curing at 90 °C or higher, vacuum mixing, and pressure before and during the setting. Although these technical procedures are beneficial to mechanical properties of UHPC, they can result in low production efficiency and high energy consumption [11]. Therefore, more and more researches have been conducted on well-chosen selection of raw materials, use of common technology, and their influences on the microstructural characteristics, mechanical properties and durability of UHPC to facilitate the production and applications of UHPC [12,13].

Until now, applications of UHPC in Europe, North America, Australia, Asia and New Zealand have been reported [14–16]. The pre-stressed hybrid pedestrian bridge, which completed in 1997 at Sherbrooke in Canada was the first engineering structure application of UHPC [17,18]. In 1997 and 1998, UHPCs were cast in beams as the first industrial application. In 2001, the first UHPC road bridge was designed and constructed at Bourg-lès-Valence in France [17,19]. However, there are numerous challenges before widespread implementation due to lack of commonly accepted standards for testing methods, design guides for engineers, and quality control methods in manufacturing facilities [20].

This review includes two parts. This part I reviews the theoretical principles, raw materials selection, mixture design, and production for UHPC, while part II reviews the hydration, microstructure, mechanical properties, dimensional stability, and durability of UHPC. It is the purpose to summarize the recent progress, to provide some insights and suggestions for further research, and to facilitate the applications of UHPC.

2. Theoretical principles for production of UHPC

2.1. Reduction in porosity

Pore structure plays an important role in determining the strength of hardened cement-based materials. The pore size distribution, shape and position of pores are also important, but it is both difficult and impractical to include all these parameters. Many experimental results have confirmed that an acceptable prediction of strength can be obtained by using total porosity. The most common relationships between porosity and compressive strength of cement-based materials are [21,22]:

Balshin's Equation:

$$\sigma = \sigma_o \cdot (1 - P)^A \tag{1}$$

Ryshkevitch's Equation:

$$\sigma = \sigma_o \cdot \exp(-BP) \tag{2}$$

Schiller's Equation:

$$\sigma = D \cdot \ln\left(\frac{P_o}{P}\right) \tag{3}$$

and Hasselmann's Equation:

$$\sigma = \sigma_o \cdot (1 - AP) \tag{4}$$

where σ_o is the compressive strength at zero porosity; P is the porosity; P_o is the porosity at zero strength; σ is the compressive strength at porosity P; A, B, and D are the experimental constants. Most other relationships are variations of one of the four types. Eq. (2) is especially suitable for low porosity systems and Eq. (3) for high porosity systems. All these four equations clearly indicated the lower the porosity is, the higher the strength is.

2.1.1. Close packing of raw materials

The porosity and pore size distribution can be effectively improved by the use of superplasticizer, incorporation of very fine reactive mineral admixtures, and close packing of raw materials, and thus improve the performance of concrete [23,24].

Many close packing models have been proposed, which can be classified into discrete and continuous models. Discrete models use idealized sets of specifically sized particles in creating packing models, represented by Furnas model [25], Aim and Goff model [26], Toufar model [27] and so on. These models were established based on binary or ternary system, and were not suitable for packing density calculation of concrete [28,29]. Stovall [30] proposed a