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Mechanical properties of ultra-high-performance fiber-reinforced concrete: A review

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A B S T R A C T

A comprehensive investigation into the mechanical properties of ultra-high-performance fiber-reinforced concrete (UHPFRC), considering various influential factors, is imperative in order to obtain fundamental information for its practical utilization. Therefore, this paper reviewed the early-age strength (or setting) development and mechanical properties of hardened UHPFRC. In connection with the latter, the effects of the curing conditions, coarse aggregate, mineral admixtures, fiber properties, specimen size, and strain-rate on the mechanical performance of UHPFRC were specifically investigated. It was obvious that (1) heat treatment accelerates the hydration process, leading to higher strength; (2) a portion of the silica fume can be replaced by fly ash, slag, and rice husk ash in mechanical perspective; (3) the use of deformed (hooked and twisted) or long straight steel fibers improves the mechanical properties at a static rate; and (4) high rate loading provides a noticeable increase in the mechanical properties. Alternatively, there are some disagreements between the results from various 'size effect' tests and the effectiveness of using twisted steel fibers at static and high rate loadings. Further research to reduce the production cost of UHPFRC is also addressed in an attempt to make its widespread use more practical.

1. Introduction

The mechanical properties of concrete, which fundamentally impact its practical use in construction sites, are highly dependent on numerous factors such as the type of cementitious materials, curing conditions, size of aggregates, rate of loading, specimen shape and size, etc. In particular, ultra-high-performance fiber-reinforced concrete (UHPFRC), which was developed in the mid-1990s, is very sensitive to these factors due to its extremely high compressive strength (in excess of 150 MPa) and flowable characteristics with high volume fractions of steel fibers (more than 2% by volume) [1,2]. To achieve such a high strength material, a low water-to-binder ratio (W/B) (normally W/B = 0.2) is applied with ultra-fine admixtures and heat treatment at 90 °C. As a result, the mechanical properties of UHPFRC are more significantly affected by the type of cementitious materials, curing condition, and aggregate size, as compared to those of ordinary concrete. In addition, because the mechanical properties of UHPFRC subjected to tensile and flexural loadings are strongly influenced by the fiber distribution characteristics, which are influenced by the casting process [3–5], the properties are also more sensitive to the specimen shape and size than those of ordinary concrete.

The superb compressive strength of UHPFRC leads to a significant reduction in the weight of structures made from this material; in general, the weight of structures consisting of UHPFRC is only one-third or one-half the weight of conventional RC structures under the same load [6]. Therefore, UHPFRC has attracted much attention from engineers who seek to produce more slender structures (e.g., applications in long-span bridge decks) with reducing the overall construction costs. However, slender UHPFRC structures are highly vulnerable to shrinkage cracking during the manufacturing stage because of their small cross-sectional areas and very steep increase of autogenous shrinkage at an early age. It is well-known that shrinkage cracking is influenced by both the rate/amount of shrinkage and also the strength (or setting) evolution. Therefore, the early-age strength evolution must be reviewed to precisely predict the shrinkage cracking behavior. Furthermore, knowing the early-age mechanical properties is important in order to determine the appropriate time for removal of forms and the amount of prestressing.

Typically, UHPFRC is not used in applications where ordinary

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concrete meets the performance criteria because of its high production cost. For this reason, achieving lower production costs is currently a key challenge for UHPFRC technology. To the best of the author's knowledge, three different methods to reduce the price of UHPFRC are currently available: (1) reducing the amount of high-strength steel fibers without deteriorating the mechanical properties (especially the tensile or flexural performance) [3,7], (2) reducing the amount of powder by using coarse aggregate [8], and (3) eliminating heat treatments or high pressure compaction [9]. These three factors clearly influence the mechanical properties of UHPFRC; thus, the effects of the steel fiber properties, coarse aggregates, and curing conditions on the mechanical properties must be addressed.

Due to its highly enhanced strength, energy absorption capacity, and unique strain-hardening behavior with multiple micro-cracks, as shown in Fig. 1, UHPFRC is considered to be a promising material for impact- or blast-resistant structures [10]. Such excellent properties can overcome the brittle nature of ordinary concrete, which often leads to an inherent poor energy absorption capacity under impact and blast loadings. The mechanical properties of concrete are influenced by the strain-rate, and the sensitivity to the strain-rate is dependent on the loading conditions and strength [11,12]. Therefore, studies involving the strain-rate effect of UHPFRC are required to be holistically reviewed.

The aim of this paper is to investigate the current state of knowledge regarding the mechanical properties of UHPFRC and to highlight some potential issues for further research. As addressed above, our attention is focused on the early-age strength (or setting) development as well as the effects of the curing conditions, coarse aggregates, mineral admixtures, fiber properties, specimen size, and loading rate on the comprehensive mechanical properties of UHPFRC.

2. Historical background of UHPFRC development

In the 1970s, the development of ultra-high-strength cement pastes with low porosity was first introduced by Yudenfreund et al. [13] and Roy et al. [14]. In Yudenfreund's study [13], a cement paste with a compressive strength of approximately 240 MPa was obtained at 25 °C after 180 days by providing a special treatment to the ground clinker with Blaine surface areas ranging from 6000 to 9000 cm^2/g and by using a low water-to-cement ratio (W/C) of 0.2. Alternatively, Roy et al. [14] obtained a cement paste with near-zero-porosity and a compressive strength of about 510 MPa by applying heat curing at 250 °C with a pressure of 50 MPa. In the early 1980s, with the development of pozzolanic admixtures and high-range water-reducing agents (i.e., superplasticizers), two different types of ultra-high-strength and low porous concretes (or pastes) were developed by Bache [15] and Birchall et al. [16] (i.e., densified with small particles (DSP) concrete and macro-defect free (MDF) pastes). DSP concrete exhibited compressive strengths ranging from 120 to 270 MPa, which were achieved by densely packing the spaces between the cement with ultra-fine particles and using an extremely low water content. Dense packing was obtained by using large quantity of superplasticizer. The concept behind MDF cement pastes was to remove macroscopic flaws during preparation; consequently, cement pastes were made with compressive strengths greater than 200 MPa and flexural strengths ranging from 60 to 70 MPa (without fiber reinforcement or high pressure compaction) [16]. Finally, in the mid-1990s, reactive powder concrete (RPC), which is the forerunner of the UHPFRCs that are currently available, was developed by Richard and Cheyrezy [17]. In their study, to achieve ultra-high strength in matrix, the size of granular materials was optimized based on packing density theory and heat (at 90 °C and 400 °C) with pressure was provided. In addition, to improve toughness of matrix, short steel fibers with a length of 13 mm and a diameter of 0.15 mm were included (1.5–3% by volume). The developed RPC exhibited compressive strengths ranging from 200 to 800 MPa and fracture energies up to 40 kJ/m^2.

3. Early-age setting and strength developments of UHPFRC

Knowing the early-age setting and mechanical strength properties of UHPFRC at any arbitrary time is important for several reasons including the removal of forms, prestressing control, and shrinkage crack control. Therefore, previous studies that investigated the early-age setting and strength development of UHPFRC are reviewed in the present study. Due to the low W/B ratio and the high fineness of the admixtures, the evaporation rate of water at exposed surfaces of UHPFRC is normally larger than that of bleeding, which causes rapid condensation of the surface even though most of the interior mortar is still fresh. This leads to plastic shrinkage cracks and durability and aesthetic problems. In particular, because of the rapid condensation of the surface, the setting evolution of UHPFRC is difficult to measure precisely. It is typically overestimated based on the penetration resistance test by ASTM C 403 [18], which is most widely used for evaluating the setting properties of fresh concrete. To overcome this problem, Yoo et al. [19] conducted several penetration resistance tests and suggested the use of paraffin oil to prevent water evaporation during the penetration resistance test. As a consequence, they obtained precise initial and final setting times for UHPFRC at 23 ± 1 °C with a relative humidity (RH) of 60± 5% of 10.8 h and 12.3 h, respectively, and the corresponding ultrasonic pulse velocities (UPVs) were determined to be 771.4 m/s and 1164.5 m/s, respectively, as shown in Fig. 2. However, the setting time varies significantly and is

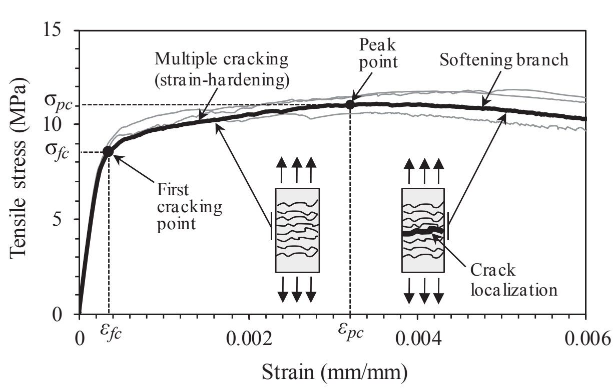

Fig. 1. Typical tensile stress versus strain behavior of UHPFRC [10].

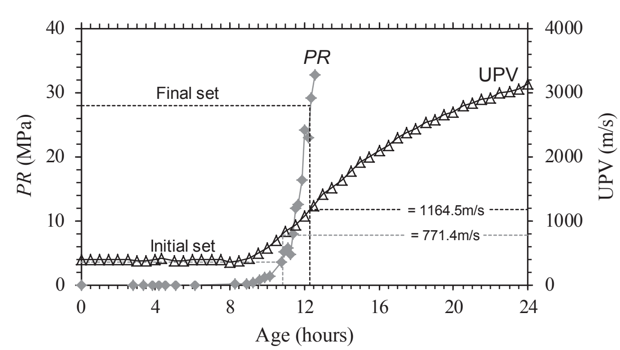

Fig. 2. Comparison of penetration resistance and UPV development [19].