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Comparative study on flexural properties of ultra-high performance concrete with supplementary cementitious materials under different curing regimes

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HIGHLIGHTS

- The compressive and flexural properties of UHPC with different GGBS or fly ash contents under standard, hot water, and steam curing were systematically studied.
- The optimal GGBS and fly ash contents for flexural behavior of UHPC were 40% and 20%, respectively, excessed which could result in a drop in flexural strength and toughness.
- Preparation of UHPC with appropriate GGBS or fly ash content under adequate standard curing offers an effective way to obtain satisfactory flexural properties.

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ABSTRACT

This study investigated the effects of curing regimes (standard, hot water, and steam curing) on mechanical properties of ultra-high performance concrete (UHPC) with different supplementary cementitious materials (SCMs). The flowability, compressive strength, flexural load-deflection relationship, ultimate flexural strength, and toughness of UHPC mixtures with 0, 20%, 40%, and 60% of either ground granulated blast-furnace slag (GGBS) or fly ash, by the mass of cement, were evaluated. Test results indicated that the increase in GGBS or fly ash content had limited or negative influence on the compressive strength of UHPC in terms of curing regime type . For the flexural strength, there existed an optimal SCM content, which was 40% for GGBS and 20% for fly ash. Excessed this dosage could result in a drop in flexural strength and toughness. The hot water and steam curing significantly improved the flexural properties. However, prolonging the standard curing over 28 d led to comparable flexural properties as those under hot water and steam curing showed. The production of UHPC with appropriate GGBS or fly ash content with adequate standard curing, therefore, offers an effective way to obtain satisfactory flexural properties.

1. Introduction

Ultra-high performance concrete (UHPC) is a new generation concrete developed based on four main theoretical principles, including reduction in porosity, improvement in microstructure, enhancement in homogeneity, and increase in toughness [1,2]. It is well known that UHPC has a very high compressive strength typically over 150 MPa, good tensile ductility and toughness, and superior durability [3–5]. Therefore, it has potential applications in bridge and industrial products as pre-cast structure members to ensure light-weighted, flexible, durable, and aesthetic structures [6,7].

To make UHPC more durable and sustainable, a high amount of supplementary cementitious materials (SCMs) and a small dosage of nanoparticles are often used to replace part of cement and/or silica fume [8,9]. High temperature curing is also adopted to accelerate the hydration of cement and enhance the secondary hydration between SCMs and $Ca(OH)_2$ [7]. The high temperature and/or pressure curing can significantly increase the overall

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properties of UHPC. Massidda et al. [10] studied the effects of autoclave curing at 180 °C on the physical properties of reactive powder concrete (RPC). The results indicated that specimens cured at 180 °C for 3 h after 3 d of pre-curing at ambient temperature reached the flexural and compressive strengths of 30 and 200 MPa, respectively. Zhang et al. [11] reported that 24 h of steam curing increased the compressive strength of RPC specimens by about 15 to 30 MPa compared to that after 28 d of room temperature curing. After 8 h of autoclave curing, RPC with 3% or 4% fiber reinforcements could achieve a compressive strength over 200 MPa. Yazici et al. [12] studied the mechanical properties of reactive powder concrete containing SCMs under room temperature, autoclave, and steam curing. They found that the compressive strength increased considerably after steam and autoclave curing, while the flexural strength and toughness decreased compared to those after room temperature curing. It was suggested that the pozzolanic activity of silica fume, crushed quartz, and the chain length of C-S-H were increased after high temperature curing [13]. Unfavorable crystalline product α-calcium silicate hydrate (α-C_2SH) can be converted to tobermorite in the presence of silica under high temperature curing. This can eventually result in decrease in porosity, improvement in strength as well as bond between matrix and aggregate/fiber [14,15]. However, high energy consumption and low production efficiency associated with high temperature curing restrict its applications. So far, extensive research on UHPC incorporated with SCMs has been conducted, but very limited information has been published about the effects of type and content of SCMs on the mechanical properties under different curing regimes [16]. If satisfied mechanical properties can be obtained with the use of high amount of SCMs under room temperature curing, this would not only facilitate the applications of UHPC but also reduce cost as well as energy consumption.

Two types of SCMs with four different contents were used in this study. The replacements of cement with ground granulated blast-furnace slag (GGBS) or fly ash were 0, 20%, 40%, and 60%, respectively. Three curing regimes, including standard, hot water, and steam curing, were adopted. The flowability and compressive strength were evaluated. Flexural load-deflection relationship, ultimate flexural strength, and toughness were used to characterize the flexural properties. The study seeks to enhance the sustainability of UHPC without sacrifice of mechanical properties.

2. Materials and experimental program

2.1. Materials

Portland cement (P.I. 42.5) complying with the Chinese Standard GB175-2007 was used [17]. Table 1 summarizes the chemical composition and density of the cement, silica fume, fly ash, and GGBS. Silica fume has an average particle size of 0.1–0.2 μm and specific surface area of 18,500 m^2/kg. The Blaine specific surface area for the fly ash and the GGBS were 427 and 410 m^2/kg, respectively. Straight smooth steel fibers with a diameter of 0.2 mm and a length of 13 mm were used. Their tensile strength is 2800 MPa. River sand with a maximum particle size of 2.36 mm were used. A polycarboxylate-based superplasticizer (SP) with a solid content of 20% was used.

2.2. Mixture proportion

Based on the previous study [9,18], UHPC with water-to-cementitious materials ratio (W/CM) of 0.18, silica fume content of 20% to 25%, straight steel fiber content of 2%, by volume of concrete, can obtain good flowability, fiber-matrix bond, and mechanical properties. Therefore, S0 or F0 incorporated with 25% silica fume and with the remaining binder as cement was selected as a reference mixture. The superplasticizer dosage was fixed at 2% by the mass of the cementitious materials. Replacements of cement with 20%, 40%, and 60% of either GGBS or fly ash, by the mass of cement in the reference mixture, were used. The UHPC mixtures incorporated with different GGBS contents were designated as S20, S40, and S60, while those with fly ash were designated as F20, F40, and F60, as summarized in Table 2.

2.3. Mixing procedure and sample preparation

During mixing, dry powders, including cement, silica fume, GGBS or fly ash, and river sand, were mixed first at a high speed for 3 min. Water and superplasticizer were then added and mixed for approximately 6 min at a low speed. Steel fibers were added slowly by passing a sieve with size of 5 mm and mixed for another 6 min until uniformly distributed.

After the flowability testing, the mixtures were cast into 40 × 40 × 160 mm molds for three-point flexural properties testing. Specimens with molds were then precured in a room at 20 °C and RH > 95% for approximately 24 h. They were then demolded and cured in the following procedures:

(1) Standard curing: cured in saturated limestone water at 20 °C until 3, 7, 28, and 90 d.
(2) Hot water curing: cured in hot water at 90 °C for 48 h.
(3) Steam curing: cured in steam at 90 °C for 48 h.

2.4. Experimental methods

2.4.1. Flowability

The flowability of all mixtures was measured in accordance with the Chinese Standard GB/T 2419-2005 [19]. The mixtures were cast into a mini cone mold and jolted for 25 times. Two diameters perpendicular to each other were then determined and mean values were reported.

2.4.2. Flexural behavior

Three-point flexural testing through displacement control was conducted. The span was 100 mm. The deflection at the center of the specimens was measured using a LVDT installed at the center of the specimens. An MTS® testing machine with 20,000 KN load cell was used. Its loading rate was set at 0.2 mm/min. Averages of three samples for each batch were reported.

Table 1
Chemical composition and density of cementitious materials.

Chemical composition	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	SO_3 (%)	MgO (%)	Na_2O_{eq} (%)	K_2O (%)	C (%)	Density (kg/m^3)
Cement	62.49	21.18	4.73	3.41	2.83	2.53	0.56	–	–	3110
Silica fume	1.85	93.90	–	0.59	–	0.27	0.17	0.86	1.06	2150
GGBS	39.11	33.0	13.91	0.82	–	10.04	–	–	–	2900
Fly ash	4.63	42.52	32.62	9.35	1.21	0.73	–	–	–	2600