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Residual compressive properties of strain-hardening cementitious composite with different curing ages exposed to high temperature

Yu Ke-quan *, Lu Zhou-dao, Yu Jiangtao

College of Civil Engineering, Tongji University, Shanghai 200092, China

HIGHLIGHTS

- The residual compressive properties of post-fire SHCC specimens were discussed.
- The influence of different curing ages was considered for post-fire SHCC specimens.
- The influence of two cooling methods was considered for post-fire SHCC specimens.
- The micro structural characterization was examined to support the test conclusions.

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ABSTRACT

This paper discussed the compressive properties of strain-hardening cementitious composite (SHCC) specimens with different curing ages varying from 1 to 28 days. The SHCC specimens exposed to four high temperatures which were 200, 400, 600 and 800 °C. The influence of different cooling methods (quenching in water and cooling in air) was also considered. The residual compressive strength and stiffness of the post-fire specimens of all curing ages generally decreased as temperatures increased. Specimens quenched in water gained better mechanical properties than those cooled in air. The micro structural characterization was examined before and after exposure to high temperature by scanning electron microscopy and the pore size distribution was obtained by mercury intrusion porosimetry. The results from the micro tests explained the mechanical properties of the post-fire SHCC specimens well.

1. Introduction

In recent years, efforts to modify the brittle nature of ordinary concrete have resulted in the concept of ultra high-performance fiber-reinforced cementitious composites (UHP-FRCC), which are characterized by tensile strain-hardening after initial cracking. Depending on its composition, its tensile strain capacity can be up to several hundred times the strain of normal and fiber-reinforced concrete. The strain-hardening cementitious composite (SHCC) is a special type of UHP-FRCC designed based on micromechanical principles to strain-harden in tension. It offers high ductility under uniaxial tensile loading and improved durability due to an intrinsically tight crack width of less than 100 μm [1,2]. During the last decade, the use of SHCC has increased considerably; it has been used in a variety of structures in various regions [3,4].

For a conventional cementitious composite, high temperature causes physical and chemical changes, resulting in deterioration of its mechanical properties, such as the compressive strength and modulus of elasticity. Mechanical properties and microstructure of a fire-damaged SHCC on 50 mm cubic specimens were assessed by Sahmaran et al. [5], and it was concluded that the mechanical performance of a fire-deteriorated SHCC suffered a significant reduction in the compressive strength and stiffness without spalling during the heating process. The role of synthetic PVA fiber and different replacement levels of fly ash (FA) on the micro structural damage and residual mechanical properties of post-fire SHCC was also considered [6]. Tahir [7] researched the specimen size effect on the residual properties of strain-hardening cementitious composites subjected to high temperature. It is concluded that the specimen size did not play an important role on the residual mechanical properties of the SHCC when the specimens were heated up to 800 °C. The stress–strain curves of different sized specimens were also found to be very similar for all the exposure temperatures.

* Corresponding author.
E-mail address: zjzjykq@163.com (Y. Ke-quan).

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Significant attention has been brought to the study of its rheological, mechanical and durability related properties of SHCC. With an increase in the application of SHCC, the risk of exposure to elevated temperatures increases as well. The behavior of SHCC exposed to high temperature has to be evaluated in particular.

Although the residual properties of SHCC after exposure to high temperatures have been studied comprehensively [5–7], there are still some aspects that should be studied. With the increased applications of SHCC in indoor environments (e.g., coupling beams in buildings), its fire performance is also a matter of concern. The mechanical properties of SHCC during the curing process and the influence of high temperature to the SHCC of different curing ages, particularly fire damage to early-age SHCC specimens, remains unknown. Similar to normal or high-performance concrete, different cooling regimes have a significant influence on the residual mechanical properties of a post-fire composite [8–11]. Hence, the main purpose of the investigation is to learn the changing tendency of compressive properties of SHCC exposed to high temperature during the whole curing age from 1 day to 28 days; especially, to check whether the early-age specimens were more vulnerable to high temperature. Furthermore, the influence of cooling regimes is also considered.

2. Experimental studies

2.1. Mix proportions and tensile properties

Table 1 shows the mix details of strain-hardening cementitious composite. Ordinary Type I Portland cement (C), Class F fly ash (FA), slica sand (maximum grain size of 180 μm and a mean size of 135 μm), tap water, polyvinyl alcohol (PVA) fibers, a polycarboxylicether type high-range water-reducing admixture (HRWR), and Hydroxypropylmethyl cellulose (HPMC) were used for SHCC. Unlike typical fiber-reinforced cementitious composites, the component characteristics and proportions within the SHCC are carefully determined with the use of micromechanical design tools to achieve the desired strain-hardening response [13]. A portion of the cement was replaced by fly ash, thereby making the mixture an eco-friendly cementitious material, to enhance the tensile strain-hardening effect. The PVA fibers with a diameter of 39 μm and a length of 12 mm are purposely manufactured with a tensile strength (1620 MPa), elastic modulus (42.8 GPa), and maximum elongation (6.0%) matching those needed for strain-hardening performance.

Table 1
Mixture properties of the SHCC.

	SHCC
Cement (C) (kg/m^3)	678
Fly ash (FA) (kg/m^3)	291
Water (W) (kg/m^3)	380
PVA fiber (kg/m^3)	26
Sand (kg/m^3)	484
HRWR (kg/m^3)	14
HPMC (kg/m^3)	1.91
W/(C+FA)	0.39
FA/C	43%
1-Day tensile strain (%)	4.2(0.38)
1-Day tensile strength (MPa)	2.1(0.12)
3-Day tensile strain (%)	4.3(0.28)
3-Day tensile strength (MPa)	3.0(0.10)
7-Day tensile strain (%)	4.4(0.14)
7-Day tensile strength (MPa)	3.3(0.20)
28-Day tensile strain (%)	4.0(0.65)
28-Day tensile strength (MPa)	4.2(0.30)

Note: Numbers in brackets are standard deviations in % and MPa for tensile strain and stress, respectively.

The direct tensile behavior of the SHCC mixtures was measured by dog-bone specimens according to JSCE [12]. The tests were conducted under displacement control at a loading rate of 0.005 mm/s. As shown in Table 1, the SHCC composites exhibited an average strain capacity of 4.0% at 28 days, with an average strength of approximately 4.2 MPa.

2.2. Test specimen preparation and testing

Specimens were removed from the molds after 1 day, and kept in a water tank until the ages of 3, 7 and 28 days. The 1-day specimens were not cured in the water, but heated immediately after 24 h of curing in the molds. The specimens of 3, 7 and 28 days were heated to 100 °C for 8 h before the heating procedure. Five specimens from each curing age were tested under compression immediately after conditioning for each curing age as control specimens.

A computer controlled furnace was used for the heating the specimens at a constant heating rate of 13.3 °C/min to reach the prescribed 200, 400, 600, and 800 °C temperature levels and then kept the target temperature for another hour to achieve a thermal steady-state condition. The temperature was measured in the air at a position above the specimen inside the furnace. After heating, the samples were subjected to two cooling regimes, cooling in air and quenching in water, given in Table 2. The test was performed under displacement control at a loading rate of 0.005 mm/s on a closed-loop controlled material testing system with a 100 kN capacity. During the compressive tests, the load and the deflection values (obtained from a pair of LVDTs attached to the test set-up) were recorded on a computerized data acquisition system. At least four samples were tested for each heating temperature and cooling regime. The compressive strengths of the unheated specimens are 8.92, 20.28, 24.20 and 30.14 MPa for the curing age of 1, 3, 7 and 28 days, respectively (see Fig. 1).

The specimens are numbered as follows: Xd-temperature-cooling regime. For example: 28d-400R(W), where 28 means the curing age of 28 days; R means cooling at room temperature; and W means quenching in water for 5 min. The weight of each specimen was measured before and after heating exposure to calculate the mass loss of fire-deteriorated specimens (see Fig. 2).

3. Experimental results and discussions

3.1. Surface and internal characteristics

In experimental studies, it is observed that when the SHCC specimens are exposed to high temperatures, some changes in color occur [14]. The specimens of all curing ages shared a similar color change when subjected to different heating temperatures. Fig. 3 shows that the color of the SHCC specimens (1d) changed from gray at 20 °C to buff at 800 °C due to the loss of water and chemical decomposition. The color of the specimens subjected to 800 °C and then quenched in water turned dark gray, which may be due to further hydration of the composite.

Surface cracks due to high temperature exposure up to 800 °C were similar for all studied curing ages of the SHCC specimens (shown in Fig. 3). Cracks became apparent after 400 °C, and

Table 2
Two cooling regimes for different curing-age SHCC specimens.

Curing ages	Temperature	Cooling in air	Quenching in water
Xd	200	√	None
	400	√	√
	600	√	None
	800	√	√