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Residual mechanical properties and spalling resistance of strain-hardening cementitious composite with Class C fly ash

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HIGHLIGHTS

- Developing green SHCC with a local industrial by-product.
- Using XRD and SEM to study influence of thermal decomposition and microcracks on compressive strength reduction.
- A tensile strain-hardening behavior after exposure to 200 °C and a strain-softening behavior after exposure to 600 °C.
- Effect of PVA fibers on residual permeability of SHCC.

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ABSTRACT

This study investigated fire resistance of strain-hardening cementitious composite (SHCC) incorporating Class C fly ash. The fly ash used is a local industrial byproduct. Adopting the local industrial byproduct would reduce the cost of SHCC significantly and reliance on overseas sources of fly ash. The results indicated that heat treatment up to 200 °C had negligible effect on strain capacity and strength of the SHCC specimens. Both compressive and tensile strengths began to deteriorate from 300 °C onwards. The SHCC specimens lost its strain-hardening feature at 300 °C and exhibited strain-softening behavior up to 600 °C. PVA fibers were found capable of increasing permeability of SHCC significantly before reaching melting point and reducing the risk of spalling under fire. This paper shows promising applications in introducing local industrial byproduct to produce green SHCC with excellent fire resistance.

1. Introduction

In recent years, efforts to improve the ductility of ordinary concrete have given birth to the concept of SHCC, which exhibits a strain-hardening behavior under tension loads with multiple cracks and produces a stress-strain curve similar to that of a ductile metal with a yielding point [1]. Due to its pseudo-strain hardening feature and fine crack width, SHCC has been observed to outperform ordinary concrete in terms of seismic performance, impact resistance, and durability [2–4]. During the past decade, SHCC has found its applications in tall buildings, bridges, tunnels, and other forms of infrastructure [5–7].

In terms of material constituents, SHCC is typically made of cement, fly ash, fine sand, water, PVA fibers and some chemical additives. There are two types of fly ash according to ASTM C618 [8], viz., Class F fly ash and Class C fly ash. The main difference between them is the content of calcium. So far, SHCC is developed using Class F fly ash which is more commonly used. In this study, Class C fly ash, a local industrial by-product, was introduced in hybrid PVA/steel fiber reinforced SHCC. Using industrial by-products to produce SHCC makes it less energy-intensive, and more environmental-friendly forming part of the circular economy effort. Meanwhile, Class C fly ash increases the resistance of concrete to sulfate attack and freezing-thawing cycles [9,10]. In addition to that, for the same fly ash content, concrete with Class C fly ash has a higher compressive strength [9] and better carbonation resistance [11] and abrasion resistance [12] than concrete made with Class F fly ash. This provides the impetus for the current research on SHCC using local by-product.

An ideal construction material should have satisfactory performance under different environmental or extreme loading conditions (explosion, impact, earthquake, fire). Fire action represents a typical accidental loading condition faced by buildings and tunnels. Addition of fly ash in concrete has been observed to improve

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strength of concrete after exposure to high temperature [13,14]. High strength fly ash concrete columns experience lesser axial deformations than high strength concrete columns under fire conditions [15]. Previous work [16–21] has contributed to a better understanding of fire resistance of Class F fly ash-based SHCC. However, fire performance of the Class C fly ash-based SHCC remains unknown. In addition to that, previous studies explained the changes in compressive strength of Class F fly ash-based SHCC from the perspective of microstructure change by using mercury intrusion porosimetry. But no specific tests were conducted to study how thermally-induced microcracks and decomposition influenced strength reduction of SHCC. As to spalling behavior, PVA fibers have been found effective to avoid explosive spalling of Class F fly ash-based SHCC under heating. It was explained that PVA fibers mitigate pore pressure and spalling risk by melting at 240 °C [16]. However, there is no experimental evidence to support this point of view. So there is also a need to study how PVA fibers mitigate explosive spalling for SHCC made with Class C fly ash.

The objective of the authors is to study residual mechanical properties of Class C fly ash-based SHCC subjected to elevated temperatures, how thermally-induced microcracks and decomposition influenced compressive strength of Class C fly ash-based SHCC, thermal spalling resistance of Class ash-based SHCC, and how PVA fibers mitigate spalling. Compressive strength tests were conducted on SHCC specimens exposed to temperature up to 800 °C at an increment of 200 °C. Tensile property tests were conducted on SHCC specimens exposed to temperature up to 600 °C at an increment of 100 °C. A smaller exposure temperature increment was chosen for residual tension tests than residual compression tests, since tensile properties of SHCC are more sensitive to temperature variation. To study the influence of thermally-induced microcracks and decomposition on compressive strength of SHCC, scanning electron microscope (SEM) and X-ray Diffraction (XRD) tests were conducted to observe the microcrack development and to investigate the change of crystal phases under elevated temperatures, respectively. To evaluate spalling resistance of SHCC and mortar under elevated temperature effect, 1D spalling tests were conducted. To understand how PVA fibers mitigate explosive spalling, residual permeability of SHCC and mortar specimens were measured after exposure to elevated temperatures.

2. Materials and methodology

2.1. Materials

The materials used in the production of SHCC mixture include ordinary Portland cement (CEM I 42.5 N) conforming to EN 197-1 [22], Class C fly ash, silica sand, water, Kuraray PVA fibers, steel fibers and a polycarboxylic-type superplasticizer. The details of the mixture are presented in Table 1. In the remaining part of the paper, unless otherwise specified, the term SHCC implies Class C fly ash-based SHCC with hybrid fibers comprising both PVA and steel fibers. The chemical compositions of the cement and Class C fly ash are given in Table 2. Particle size distributions of cement, Class C fly ash, and silica sand are shown in Fig. 1. The specifications of PVA fibers and steel fibers are given in Table 3. It should be noted that the surface of PVA fiber is coated with 1.2% proprietary oiling agent.

Table 2
Chemical compositions of cement and Class C fly ash.

Chemical composition	Cement	Fly ash
SiO_2, %	24.27	40.80
Al_2O_3, %	4.56	11.54
Fe_2O_3, %	3.95	9.94
K_2O, %	0.55	1.06
CaO, %	62.20	23.92
MgO, %	3.34	4.84
SO_3, %	–	3.69
Na_2O, %	0.21	0.90

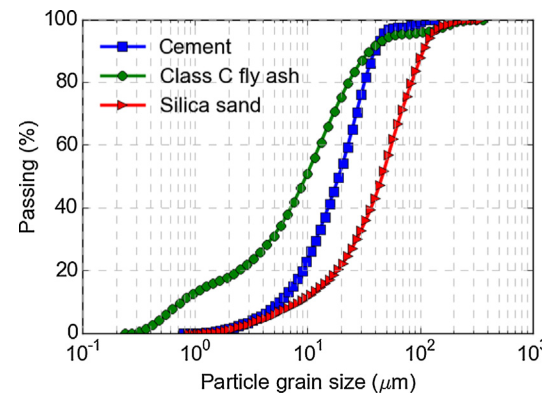

Fig. 1. Particle size distributions of cement, Class C fly ash, and silica sand.

Table 3
Specifications of PVA and steel fibers.

Fiber	PVA	Steel
Tensile strength, MPa	1060	2000
Diameter, μm	38	160
Length, mm	12	13
Elastic modulus, GPa	42.8	200
Density, kg/m^3	1300	7800
Melting point, °C	240	1370
Elongation	6.5%	–

2.2. Specimen preparation

SHCC mixture was prepared in a 20 L Hobart mixer. Cement, fly ash, and silica sand were dry mixed for 5 min. After that, water and superplasticizer were added and mixed for 5 min to achieve good workability. Finally, PVA and steel fibers were sequentially added in and stirred for 3 min to ensure homogeneous distribution in the mixture.

Cube specimens (50 mm) were prepared for compressive strength tests and dog-bone specimens (Fig. 2) were prepared for direct tensile tests. Two 200 × 200 × 140 mm block specimens were used for 1D spalling test. One specimen was made of SHCC, and the other made of mortar. The mix proportion of mortar was the same as SHCC except that mortar specimens had no fibers. Six Φ150 × 40 mm disk specimens were cast for permeability measurement, three of which were made of SHCC and the other three made of mortar. The purposes of 1D spalling tests and permeability tests were to study the spalling resistance of SHCC with

Table 1
Mix proportion of SHCC (kg/m^3).

Cement	Fly ash	Silica Sand	Water	PVA fiber	Steel fiber	Superplasticizer
289	866	404	369	19.5	78	15.2