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Specimen size effect on the residual properties of engineered cementitious composites subjected to high temperatures

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ABSTRACT

In this study, size effect on the residual properties of Engineered Cementitious Composites (ECC) was investigated on the specimens exposed to high temperatures up to 800 °C. Cylindrical specimens having different sizes were produced with a standard ECC mixture. Changes in pore structure, residual compressive strength and stress–strain curves due to high temperatures were determined after air cooling. Experimental results indicate that despite the increase of specimen size, no explosive spalling occurred in any of the specimens during the high temperature exposure. Increasing the specimen size and exposure temperature decreased the compressive strength and stiffness. Percent reduction in compressive strength and stiffness due to high temperature was similar for all specimen sizes.

1. Introduction

Engineered Cementitious Composite (ECC) is a newly developed, high-performance fiber-reinforced cementitious composite with substantial benefits; 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 ECC has considerably grown up, and it was used in a variety of structures such as high-rise buildings, bridges, tunnels, highways, and other forms of infrastructures in North America, Europe and Asia, [3,4]. Significant attention has been brought to the study of its rheological, mechanical and durability related properties of ECC. The behavior of ECC exposed to high temperature has in particular to be evaluated. When a cement based composite is exposed to high temperature, it causes a material degradation in the form of strength decrease, cracking, and in some cases, spalling [5]. Mechanical properties and microstructure of fire-damaged ECC on 50 mm cubic specimens were assessed by Sahmaran et al. [6], and in that study it was concluded that the mechanical performance of fire-deteriorated ECC mixture is similar to or better than that of conventional concrete incorporating polypropylene or steel fibers. Although there was a significant reduction in compressive strength and stiffness, no explosive spalling was observed in any cubic ECC specimens during the fire test. The promising performance of ECC under fire exposure may be attributed to the presence of PVA fibers and high-volume fly ash (FA) [6]. In their further research [7], they tried to understand the role of synthetic PVA fiber and different replacement levels of fly ash (FA) on the microstructural damage and residual mechanical properties of ECC after exposed to high temperatures. They concluded that incorporating PVA fiber seems to be a promising way to enhance the resistance of matrix to thermally induced explosive spalling, and increasing FA content from 55% to about 70% provides ECC with better residual mechanical properties after exposure to temperatures from 200 to 600 °C.

As it is well known, the strength of brittle and defect-sensitive materials such as concrete depends to a significant extent upon the volume of the tested specimen [8]. This phenomenon is commonly referred to as “size effect” and reflects the fact that the probability of finding a crack of critical size and orientation increases with the number of cracks, i.e. with the volume of the specimen [9,10]. A review of the literature also showed that the risk of explosive thermal spalling increases with the increase in specimen size. This is due to the fact that specimen size has a direct effect on the rate of heat and moisture loss and the moisture content at the time of testing [11,12]. For example, a smaller size specimen provides a shorter path for moisture to escape during the fire test, thereby reducing spalling forces Therefore, careful consideration must be given to the size of specimens when evaluating the high temperature resistance and spalling behavior of cement-based composites.

As discussed above, although the residual properties of ECC after exposure to high temperatures have been studied comprehensively, the influence of specimen size on the residual properties, cracking and spalling of ECC has not been studied. The research described in this paper aimed to gain a better

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understanding of the influence of the specimen size on the behavior of ECC specimens exposed to elevated temperatures. For this purpose, standard ECC mixture, known also as ECC M45 and has a fly ash–cement ratio of 1.2, by weight, was used. In order to find out the effect of specimen size on the behavior and residual properties of ECC mixtures exposed to high temperatures (up to 800 °C), ECC specimens having dimensions of ∅50 × 100 mm, ∅100 × 200 mm and ∅150 × 300 mm were tested. Microstructure, spalling, residual compressive strength and stress–strain curves of fire deteriorated ECC specimens were examined.

2. Research significance

The effects of high temperatures on the residual mechanical and microstructural properties of ECC had been widely researched. However, to the best of the author's knowledge, there is no investigation on the effect of specimen size on ECC behavior at high temperatures. A greater understanding of its fire performance will improve confidence in its use in civil engineering projects. This research adds important contribution to existing information on the behavior of ECC under elevated temperatures.

3. Experimental studies

3.1. Materials, mix proportions and basic mechanical properties

Standard ECC mixture (M45) with a fly ash–cement ratio (FA/C) of 1.2 by mass was used in this investigation, details of which are given in Table 1. The materials used in the production of standard ECC mixture were Type I Portland cement (C), Class F fly ash (FA), sand, water, polyvinyl alcohol (PVA) fibers, and a polycarboxylic-ether type high-range water-reducing admixture (HRWR). Chemical composition and physical properties of cement and FA are presented in Table 2. Unlike typical fiber-reinforced cementitious composites, the component characteristics and proportions within the ECC are carefully determined with the use of micromechanical design tools to achieve the desired strain-hardening response [13]. To minimize the mortar matrix fracture toughness, no large aggregates were used, and the silica sand had an average grain size of 110 μm and a maximum size of 200 μm. The PVA fibers with a diameter of 39 μm and a length of 8 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. Additionally, the surface of the PVA fibers is coated with a proprietary oiling agent 1.2% by mass to tailor the interfacial properties between fiber and matrix for strain-hardening performance [13].

ECC mixture was prepared in a standard mortar mixer at water to cementitious material ratio of 0.27. HRWR was added to the mixture until the desired fresh ECC characteristics were visually observed [14]. To characterize the direct tensile behavior of the ECC mixtures, 152 × 76 × 13 mm coupon specimens were used. Direct tensile tests were conducted under displacement control at a loading rate of 0.005 mm/s. The typical tensile stress–strain curves of ECC mixtures at 28 days are shown in Fig. 1. As seen from the figure, after first cracking, the uniaxial tensile stress increased at a slower rate, along with the development of multiple cracks with small crack spacing and tight crack widths. The ultimate tensile strain and uniaxial tensile strength capacity of ECC mixture at 28 days are listed in Table 1. As seen in Table 1, the ECC composite exhibited a strain capacity of 2.7% at 28 days. After direct tensile testing, all residual crack widths were also measured in the unloaded stage on the surface of the specimens using a portable microscope. All of the ECC coupon specimens showed multiple cracking behavior with small crack spacing and tight crack widths (<70 μm).

3.2. Test specimen preparation and testing

To investigate the influence of size effect on pore structure, residual compressive strength and stress–strain curve of ECC, several cylindrical specimens having a constant length-to-diameter ratio of two and dimensions of ∅50 × 100 mm, ∅100 × 200 mm and ∅150 × 300 mm were cast. The choice of maximum cylindrical specimen size (∅150 × 300 mm for this study) was limited by the size of the furnace to be used in the heating process. Specimens were removed from the molds at 1 day, and kept in a climatic chamber until the age of 28 days at 23 ± 2 °C and 95 ± 5% RH. At 28 days, six specimens from each size were tested under compression immediately after conditioning; these control specimens will be referred to as those tested after exposure to normal curing condition (unheated). Before testing, both ends of the cylindrical

Table 1
Mixture properties of ECC.

	ECC
Cement (C) (kg/m^3)	558
Fly ash (FA) (kg/m^3)	669
Water (W) (kg/m^3)	326
PVA fiber (kg/m^3)	26
Sand (kg/m^3)	446
HRWR (kg/m^3)	2.3
W/(C + FA)	0.27
FA/C	1.2
28-Day tensile strain (%)	2.7
28-Day tensile strength (MPa)	5.1

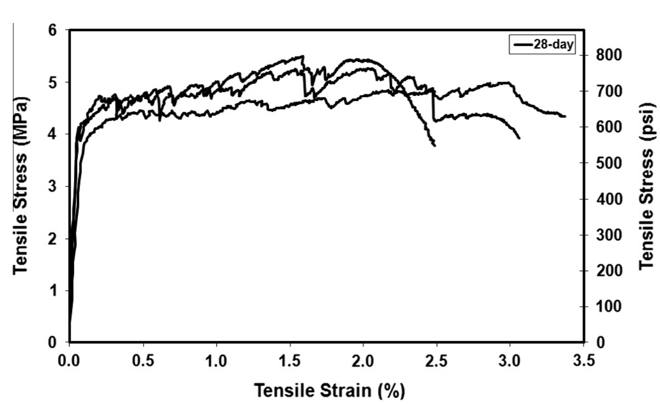

Fig. 1. Typical tensile stress–strain response of standard ECC mixture (M45).

Table 2
Chemical composition and physical properties of cement and fly ash.

	Chemical composition (%)									Physical properties		
	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	LOI	Spec. grav.	Ret. on 45 μm (%)	Water req. (%)
Cement	61.8	19.4	5.3	2.3	0.9	3.8	1.1	0.2	2.1	3.15	12.9	–
Fly ash	5.6	59.5	22.2	3.9	–	0.2	1.1	2.7	0.2	2.18	9.6	93.4