Cement and Concrete Composites 70 (2016) 153–158

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Ultra-high-ductile behavior of a polyethylene fiber-reinforced alkali-activated slag-based composite

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ARTICLE INFO

Article history:
Received 9 October 2015
Received in revised form
6 April 2016
Accepted 11 April 2016
Available online 13 April 2016

Keywords:
Alkali activator
Composite
Ground granulated blast furnace slag
High ductility
Polyethylene fiber

ABSTRACT

This paper presents an experimental study of the meso-level composite properties of an ultra-high-ductile polyethylene-fiber-reinforced alkali-activated slag-based composite. Four mixtures with 1.75 vol% of polyethylene fibers were prepared with varying water-to-binder ratio. The viscosity of the matrix was controlled to ensure a uniform fiber dispersion. A series of experiments, including density, compression, and uniaxial tension tests, was performed to characterize the mechanical properties of the composite. The test results showed that the average tensile strength to compressive strength ratio of the composites was 19.8%, nearly double that of normal concrete, and the average crack width was 101 μm. It was also demonstrated that tensile strain capacity and tensile strength of up to 7.50% and 13.06 MPa, respectively, can be attained when using the proposed polyethylene-fiber-reinforced alkali-activated slag-based composites.

1. Introduction

The repair and rehabilitation of aged and deteriorated structures have become important issues in the field of construction engineering [1]. In addition, the magnitude and number of natural and man-made hazards appears to be growing. To address these issues, there is a need for technological advances that improve either the condition or performance of the members of existing structures. High-performance fiber-reinforced cementitious composites (HPFRCCs) such as high-ductile cementitious composites and ultra-high performance concrete (UHPC) have been developed to meet this technical demand [2–6]. Engineered cementitious composites (ECC) represent a unique class of HPFRCCs which are micro-mechanically tailored to feature high intrinsic tensile ductility levels with moderate amounts of fiber. Polyvinyl alcohol (PVA)-ECC shows an ultimate strain level which exceeds 4%, i.e., nearly 400 times that of concrete, as well as an ultimate strength of 4.5 MPa for composites when a moderate fiber volume fraction of 2.0% is used [7]. Recently, high-strength and high-ductility (HSHD) concrete, which is a type of UHPC, was developed. Tests of this material demonstrated a strength level similar to that of normal UHPC. The compressive strength was 166 MPa, the first-cracking strength was 8.3 MPa, and the tensile strength was 14.5 MPa. The superiority of this material was proven in tests of its tensile strain capacity, which was as high as 3.4%, which is 34 times higher than that of commercial UHPC [8,9]. In most types of HPFRCC, cement is used as the main binder. However, it is well known that the CO_2 produced by the cement industry accounts for up to 7% of global manmade CO_2 [10]. Therefore, the production of ordinary Portland cement (OPC) is considered to be one of the significant contributors to global warming.

Since the 1960s, many studies have been carried out to develop cementless slag- or geopolymer-based alkali-activated mortar and concrete and to investigate the mechanical and chemical properties of these materials in an effort to reduce the use of cement in the construction industry [11–16]. Previous studies reported that alkali-activated concrete has advantages over OPC concrete, such as high strength development at early and long-term ages, high resistance to chemical attacks and freeze-thaw cycles, and lower carbonation rates [11,13]. However, previous studies also reported that alkali-activated mortar or concrete shows brittle behavior and is susceptible to cracking, similar to OPC mortar or concrete [17,18].

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http://dx.doi.org/10.1016/j.cemconcomp.2016.04.002
0958-9465/

The improvement in the ductility of alkali-activated cementless mortar and concrete with self-controlled crack widths by the incorporation of the proper fibers represent another technical advancement in terms of durability and resilience as well as a 'green' material development. Lee et al. established the feasibility of developing a strain-hardening fiber-reinforced cementless composite using a mortar based on alkali-activated ground-granulated blast furnace slag (GGBS) and PVA fibers [19]. It was demonstrated that tensile strain-hardening behavior and ductility as high as 4.5% can be attained. Specifically, for three mixtures with different alkali activators and water-to-binder ratios, the compressive strength ranged from 19.4 MPa to 30.6 MPa, the tensile strain capacity ranged from 1.53% to 4.48%, the first-cracking strength ranged from 2.55 MPa to 3.87 MPa, and the tensile strength ranged from 2.83 MPa to 4.69 MPa at 28 days. Ohno and Li established the feasibility of strain-hardening fiber-reinforced fly-ash-based geopolymer composites with high tensile ductility and a tight crack width [20]. The compressive strength, tensile strength and tensile ductility of the composite were 27.6 MPa, 3.4 MPa, and 4.3%, respectively. Nematollahi et al. also developed relatively high-strength PVA-fiber-reinforced engineered geopolymer composites [21,22]. The compressive strength, tensile strength and tensile ductility of these composites were 63.7 MPa, 4.7 MPa, and 4.3%, respectively. Although it was demonstrated that a cementless alkali-activated composite reinforced with PVA fibers has tensile ductility as high as that of cement-based HPFRCC, the literature on the mechanical properties of cementless alkali-activated composites reinforced by other types of fibers is fairly limited. The polyethylene (PE) fiber has hydrophobic surface property and higher tensile strength than PVA fiber.

The purpose of this study is to improve the composite properties of fiber-reinforced alkali-activated slag-based composites by adopting PE fiber and optimizing the mixture proportion and to experimentally investigate the ultra-high tensile ductility of the new composite.

2. Materials and methods

2.1. Materials and mixture proportion

The materials and mix proportions investigated in this study are listed in Table 1. The GGBS and the alkali activator, composed of calcium hydroxide and sodium sulfate, which come in powder form to prevent quick setting, were used as binding materials. The binder type was fixed in this study. The amounts of the alkali activators, i.e., calcium hydroxide and sodium sulfate, were respectively 8.38% and 3.35% of the source material (GGBS) in terms of the mass ratio. The Blaine fineness of the GGBS used in this study was 4320 cm^2/g. The specific gravity of the GGBS was 2.92. Table 2 gives the chemical composition of the GGBS as measured in an x-ray fluorescence (XRF) analysis. The mixtures are designed to investigate the effect of the water-to-binder ratio on the properties of the composite. Aggregates, which lead to higher matrix toughness, are excluded from the mixture design for all mixtures. Using the approach suggested by Li and Li [23], optimized amounts of a high-range water-reducing admixture (HRWRA) and a viscosity-modifying agent (VMA) was used to achieve the proper rheology to ensure uniformity of the fiber dispersion. PE fiber was used as a reinforcement material in all mixtures. The properties of the PE fiber used in this study are listed in Table 3.

Table 1
Mix proportions.

Mixture	Binder	Water	HRWRA	VMA	Antifoamer	Fiber (vol%)
M26	1	0.26	0.024		0.001	1.75
M30	1	0.30	0.009		0.001	1.75
M34	1	0.34	0.004	0.0001	0.001	1.75
M38	1	0.38	0.002	0.0003	0.001	1.75

Note: All numbers are mass ratios of binder weight except fiber contents (volume fraction).

2.2. Mixing, casting, and curing of specimens

Each of the compositions described above was mixed in a Hobart mixer. Solid ingredients, including the GGBS and alkali activators, were added to the mixer, with the mixing process then continuing for approximately 3 min. Water was slowly added and the mixture was then mixed for another 3 min. Next, HRWRA and VMA, if necessary, were added to the mixer to achieve the proper viscosity of the matrix. Once a consistent mixture was reached, the fiber was gradually added, taking care to ensure a uniform fiber dispersion. The entire mixing procedure for each batch generally took 10 min. Afterwards, the mixture was cast into molds (four specimens for the uniaxial tension test and three 50-mm cubes for the cube compression test) while moderate vibration was applied. The molds were covered with plastic sheets and cured in air at room temperature (23 °C ± 3 °C) for two days. The hardened specimens were then removed from the molds and cured in water for 28 days in a laboratory room at a temperature of 23 °C ± 3 °C.

2.3. Density test

The hardened densities, ρ, were calculated by measuring the weights of the samples in air, W_{AIR}, and in water, W_{WATER}. The cubes were tested at 28 days in a water-saturated state with the excess water wiped from the surfaces.

$$\rho = \frac{W_{AIR}}{W_{AIR} - W_{WATER}} \times \rho_w \quad (1)$$

here, ρ_w is the density of water, which is assumed to be 1 g/cm^3.

2.4. Mechanical tests

The compressive strength was measured using the 50-mm cube specimens according to ASTM C109-07 [24]. To investigate the behavior of the composites under tension, uniaxial tension tests were performed using an electronic universal testing machine according to JSCE recommendations [25]. The tests were performed under displacement control with a loading speed of 0.1 mm/min, and the loading force and elongation were measured. Two linear variable differential transducers (LVDTs) were attached to both sides of the center of the tensile specimen in order to monitor the elongation. The gage length (80 mm) for each specimen was measured during the test setup, as shown in Fig. 1(b), before starting the tension test to avoid errors during the calculation of the tensile strain from the deformation. The dimensions of the cross-section within the gage length were 30 mm × 13 mm. Fig. 1 shows the specimen geometry and the test setup. In addition to the tensile stress–strain curves, the tensile strength was measured, as was the ultimate tensile strain. Four specimens were tested in order to check the variability of the performance under tension.

3. Results and discussion

3.1. Density

Table 4 presents the hardened densities of each composite as calculated by measuring the weight of three cubes in a water-