Composite Structures 138 (2016) 116–121

Contents lists available at ScienceDirect

Composite Structures

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

Composite properties of high-strength polyethylene fiber-reinforced cement and cementless composites

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ARTICLE INFO

Article history:
Available online 30 November 2015

Keywords:
Alkali-activator
Cement
Composite
Polyethylene fiber
Slag

ABSTRACT

This paper presents an experimental study of the composite properties of cement based- and alkali-activated ground-granulated blast furnace slag (GGBS) based composites reinforced by high-strength polyethylene fibers and a discussion of the different behaviors of the two types of binder-based composites. A series of experiments, including those to test the density, compression, and uniaxial tension, was performed to characterize the mechanical properties of the composite. The test results indicated that an alkali-activated GGBS composite shows a higher tensile strain capacity with smaller crack widths and crack spacings than a cement-based composite, although the alkali-activated GGBS composite showed lower compressive and lower tensile strength than the cement-based composite with the same water-to-binder ratio. It was also observed that the alkali-activated GGBS-based composite has higher ratio of the tensile strength to the compressive strength than the cement-based composite.

1. Introduction

Research on alkali-activated mortar and concrete is highly active, and many studies have been conducted to develop cementless types of concrete and to investigate the mechanical, physical, and chemical properties of these materials [1–6]. Furthermore, the commercial-scale deployment of alkali-activated cement and concrete is now proceeding rapidly in multiple nations [7]. Recently, high-ductile-fiber reinforced alkali-activated ground-granulated blast furnace slag (GGBS) and fly ash-based cementless composites have been developed to improve the brittleness of the materials used in these cases and to achieve technical advancements in terms of durability and resilience as well as green materials development [8–11]. Previous work reported that a compressive strength of 30.6 MPa, a tensile strength of 4.7 MPa, and a tensile strain capacity of 4.5% are attainable by alkali-activated GGBS and PVA fibers while a compressive strength of 27.6 MPa, a tensile strength of 3.4 MPa, and a tensile strain capacity of 4.3% are also attainable by alkali-activated fly ash-based geopolymer and PVA fibers [8,10]. More recent work also showed that a high compressive strength up to 63.7 MPa while maintaining a high tensile strain capacity of 4.3% can be achieved by optimizing the type of alkali-activator, the mixture proportion, and the curing conditions [11].

Although it was demonstrated that a PVA-fiber-reinforced alkali-activated composite has tensile ductility as high as that of a cement-based high-ductile composite, the literature on the engineering properties of alkali-activated composites reinforced by other types of fibers and a comparison between a cement-based composite and an alkali-activated composite are fairly limited. The purpose of this study is experimentally to investigate the composite properties of the compressive strength, tensile strength, and tensile strain capacity of cement-based and alkali-activated GGBS-based composites reinforced by high-strength polyethylene (PE) fiber and to discuss the different tensile behaviors of the two types of binder-based composites.

2. Materials and methods

2.1. Materials and mixture proportion

The mixture proportions including materials used in this study are listed in Table 1. Cement and alkali-activated GGBS were used as the binding materials. A powder type of alkali activator composed of calcium hydroxide and sodium sulfate was used because the liquid type of alkali activator induces quick setting [12]. The types of cement and alkali-activated GGBS binder were fixed in this study. Two types of alkali activators composed of

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http://dx.doi.org/10.1016/j.compstruct.2015.11.046
0263-8223/

Table 1
Mix proportions.

Mixture	Binder		Water	SP	VMA	Anti-foaming agent	Fiber (vol.%)
	Cement	AAS					
C34	1		0.34	0.0007	0.0002	0.001	1.75
C38	1		0.38		0.0002	0.001	1.75
S34		1	0.34	0.004	0.0001	0.001	1.75
S38		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).

calcium hydroxide of 8.38% and sodium sulfate of 3.35% of GGBS in mass ratio were used for activating GGBS. The Blaine fineness values, specific gravity values, and the chemical compositions of the binding materials are listed in Table 2. The chemical composition of cement and GGBS was measured in an X-ray fluorescence (XRF) analysis. The mixtures were designed to investigate the effects of the type of binding materials and the water-to-binder ratio on the properties of the composite properties. In order to compare the properties of paste-based composite between cement and alkali-activated GGBS, aggregates are excluded because those may influence the properties of matrix and lead to higher matrix toughness. A superplasticizer (SP) and a viscosity-modifying agent (VMA) was used to achieve the proper viscosity for good fiber dispersion [13]. Anti-foaming agent, which is a mixture of surface active and mineral substances, containing no silicones, was included to minimize the amount of air bubbles and ensure an escape of air entrapped during mixing process. Table 3 gives the dimensions and properties of PE fiber used in this study. The tensile strength of the PE fiber is about two times higher than that of PVA fiber [8].

2.2. Mixing, casting, and curing of specimens

Powder type binders, i.e., the cement or alkali activators and GGBS, were added to a Hobart type mixer and mixed for 2 min. Next, water, SP, VMA, and antifoamer were sequentially added and the mixture was mixed for another 5 min. Once a mixture became consistent and had proper viscosity, the fiber was gradually inserted into the mixer. The mixture including fiber was mixed to ensure a uniform fiber distribution for approximately 3 min. After mixing, each mixture was cast into molds. Four tension specimens and three cubes were made for the uniaxial tension test and compression test, respectively. The molds were covered with plastic sheets to minimize the evaporation of water and cured in air at room temperature of 23 °C ± 3 °C. After two days, the molds were removed and the hardened specimens were cured in water at temperature of 23 °C ± 3 °C until 28 days.

2.3. Density test

The hardened densities of mixtures, ρ, were obtained from Eq. (1) by measuring the weights of the specimens in air, W_A, and in water, W_W The specimens were measured at 28 days in a saturated-surface-dry state.

Table 3
Properties of the fibers.

Type of fiber	Diameter (μm)	Length (mm)	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation (%)
PE	16	12	3030	112	3.3

$$\rho = \frac{W_A}{W_A - W_W} \times \rho_w \quad (1)$$

Here, ρ_w is the density of water (1 g/cm^3).

2.4. Mechanical tests

The compressive strength was measured on cube specimens measuring 50 mm × 50 mm × 50 mm according to ASTM C109-07 [14]. To characterize the tensile behavior of each tension specimen, uniaxial tension tests were performed on the specimens with dimensions recommended by JSCE using an electronic universal testing machine under displacement control at a loading speed of 0.1 mm/min [15]. During the tests, the loading force and elongation were measured. Two linear variable differential transducers were attached to both sides of the center of the tensile specimen to measure the elongation. The gage length 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 of specimens within the gage length of 80 mm were 30 mm × 13 mm. Fig. 1 shows the geometry of tension specimen and the setup of test.

3. Results and discussion

3.1. Density

Table 4 presents the average values of measured densities for three cube specimens. As expected, the density decreased with an increase in the water-to-binder ratio and the densities of alkali-activated GGBS-based composites were lower than those of cement-based composites with the same water-to-binder ratio. Theoretical values of densities calculated from the density of each composition and its proportion were 2.02 g/cm^3, 1.96 g/cm^3, 1.94 g/cm^3, and 1.89 g/cm^3 for C34, C38, S34, and S38, respectively. It was exhibited that the error rates were less than 3.1%. From the density test results, it can be concluded that the composite can be successfully made without unintentional pores by the mixing method.

3.2. Compressive strength

The compressive strength of each mixture is listed in Table 5. S34 and S38 showed lower compressive strength levels by 43.3% and 48.6%, respectively, compared to those of C34 and C38 with the same water-to-binder ratio. C38 and S38, with a water-to-binder ratio of 38%, showed lower compressive strength by 19.9% and 27.3%, respectively, compared to those of C34 and S34 with a

Table 2
Properties of cement and GGBS.

Material	Specific surface area (cm^2/g)	Density (g/cm^3)	Chemical composition (%)								
			SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	TiO_2	K_2O	etc.
Cement	3297	3.14	18.5	4.5	3.3	65.8	3.4	2.2	0.3	1.1	0.9
GGBS	4320	2.92	31.5	13	0.5	44.6	4.9	3.4	0.8	0.5	0.8