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Mechanical properties and mechanisms of fiber reinforced fly ash–steel slag based geopolymer mortar

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HIGHLIGHTS

- The optimum content of PP, BF and SF fiber on geopolymer mortar.
- Effects of fiber on compressive and flexural strength and force-displacement curve.
- Reinforcing mechanism investigated by SEM and BET.

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ABSTRACT

Fly ash–steel slag based geopolymer was studied with the aim of recycling solid wastes, and developing a sustainable alternative to Portland cement. This paper studies the effects of fibers on mechanical properties of geopolymer. SEM and BET measurements were conducted to investigate the reinforcing mechanism. The results show that polypropylene fiber and basalt fiber can improve the mechanical properties at the late age, and steel fiber shows excellent toughening and reinforcing effects on geopolymer. SEM and BET results indicate that fibers could relieve the stress concentration, increase the specific surface area and significantly decrease the average pore diameter of geopolymer.

1. Introduction

Geopolymers are inorganic aluminosilicate polymeric material formed by polymerization of aluminosilicate precursors with alkaline solutions, which set and harden at near ambient temperatures [1–3]. The new concrete based on alkali-activated material is beneficial for climate change issues. The production of geopolymer materials does not need to calcine or sinter raw materials at a high temperature, only parts of raw materials need to be baked or pretreated at a relative low temperature, and geopolymerization processing can be finished at room temperature to 150 °C, and the production process has almost no NOx, SOx, and CO production, CO_2 emissions are also very low [4]. They could contribute to the overall objective of reducing the CO_2 emissions by 1/4 associated with the concrete production [5]. On the other hand, geopolymers have excellent properties such as high early strength, durability against chemical attack, higher fire resistance, and immobilizing of heavy metals. It has been widely used in building materials, nuclear waste disposal and aerospace materials, the interest in this cementitious material is increasing and it is now seen as an alternative to conventional Portland cement [6–8]. However, like most ceramics, it suffers from quasi-brittle characters and low flexural strength [9–11], and incorporation of fiber into the cementitious matrix is a well-known method to enhance the mechanical properties.

Fiber used to reinforce materials can be placed into two categories [12–15]: low modulus, high elongation fibers such as nylon, polypropylene and polyethylene in which the fibers primarily enhance the energy absorption characteristics; High strength, high modulus fibers such as steel fiber and glass fiber, in which the fibers enhance the strength, as well as the toughness of the matrix. Reed et al. [16] found that the addition of polypropylene fiber generally improved the compressive strength and ductility of geopolymer concrete. Ranjbar et al. [17] also mixed polypropylene fiber into fly ash based geopolymer, they found that incorporation of polypropylene fiber would reduce workability in early ages by

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studying its shrinkage changes and mechanical properties. The addition of polypropylene fiber is not beneficial to its early strength growth, even delays its growth due to poor surface compatibility between polypropylene fiber and the matrix. However, the toughness and energy absorption of the material are improved.

Luo et al. [18] investigated the mechanical properties of basalt fiber reinforced geopolymer concrete. The experiment results showed that the compressive strength reached the highest level when basalt fiber content was 0.3% (volume ratio), and the increase was 37.76%, 34.82% and 31.52%, respectively, at 3 d, 7 d and 28 d; The flexural strength reached the highest level when basalt fiber content was 0.1% (volume ratio), and the growth factor was 16.67%, 16.22% and 22.22%, respectively, at 3 d, 7 d and 28 d. Xu et al. [19,20] used slag and fly ash as raw materials to prepare the geopolymer and studied the deformation characteristics of it under impact load. The results showed that the optimum basalt fiber content was 2% (volume ratio).

The steel fiber was also used to improve the energy absorption, tensile strength of the fly ash based geopolymer. When the fiber content was 3% (volume ratio), the geopolymer had the best toughening strength which reached 27 MPa and 35 MPa at 7 d and 56 d respectively [9].

In summary, while a number of authors have examined the development and performance of fiber reinforced geopolymer and focused on geopolymer materials with single geopolymer binders, to this day, there are few papers reported the mechanical and microstructural characteristics of fiber reinforced geopolymer mortar (FRGM). In this paper, fly ash and steel slag have been used together for the production of a binary geopolymer matrix, then the effect of volume contents and the type of fibers on the mechanical properties of geopolymer mortar were studied. The reinforcing mechanism was explored by Scanning electron microscope (SEM) and Brunauer-Emmett-Teller (BET) technology.

2. Experimental

2.1. Materials

Fly ash and steel slag were used as the main raw materials in the current study to prepare the geopolymer binder, and sand (The river sand with a fineness modulus of 3.1.) was used as a fine aggregate. The specific surface area of fly ash is about 369 m^2/kg; Its chemical composition is shown in Table 1, mainly 22.40% of Al_2O_3, 40.70% of SiO_2 and 9.46% of CaO, close to the high calcium fly ash (CaO > 10%), which is belong to Class C fly ash. Steel slag is the solid waste discharged from steelmaking, and its content is affected by factors such as iron ore source, slagging material and steelmaking process. The specific surface area of steel slag is 400 m^2/kg; The main chemical composition of steel slag is CaO, SiO_2, Fe_2O_3 and MgO (Table 1).

In this paper, the modulus of sodium silicate solution (M = n (SiO_2)/n (Na_2O)) is 1.5, which was adjusted by NaOH and used as composited alkali activator. The precise composition of the 2 alkali solutions is: 91.34% sodium silicate solution and 9.66% NaOH by mass.

Polypropylene fiber (PP fiber) of 12 mm in length and 18–30 μm in diameter was used in this paper (Fig. 1(a)). Basalt fiber (BF) with a length of 12 mm and a diameter of 7–30 μm was used (Fig. 1(b)). Steel fiber (SF) with a length of 13 mm and a diameter of 0.2 mm were used (Fig. 1(c)).

2.2. Mix proportions of FRGM

Mix proportions of FRGM are presented in Table 2. The ratio of water to binder is 0.4 (include the water in activator), the ratio of binder to sand is 1:2.5, the equivalent of Na_2O in activator to the binder material is 10%. The samples with 0.1% (All the proportions are expressed in volume ratio (%)) PP fiber (PP-1), 0.2% (PP-2), 0.3% (PP-3), 0.4% (PP-4) were selected and compared with control sample. The samples with 0.1% basalt fiber (BF-1), 0.2% (BF-2), 0.3% (BF-3), 0.4% (BF-4) and 0.5% (BF-5) were selected and compared with control sample. The samples with 0.1% steel fiber (SF-1), 0.2% (SF-2), 0.3% (SF-3), 0.4% (SF-4) and 0.5% (SF-5) were selected and compared with control sample.

2.3. Preparation of FRGM

Preparation of FRGM process was similar to the process of cement mortar preparation. (1) Put fibers into the activator solution and mixed evenly, poured them into the mixing pot and added water, fly ash and steel slag. (2) Mixed them 60 s in the cement mortar mixer with low-speed. Then, added sand evenly within 30 s and high-speed mixed for 30 s, then stop 90 s. Scraped the mortar from the leaves into mixing pot within 15 s and high-speed mixed for 60 s. (3) Poured the mortar into the 40 × 40 × 1 60 mm and 78 × 22.5 × 22.2 mm dog-bone moulds, gently vibrated them several times, vibrated in the cement mortar vibration table to remove bubbles. (4) Demold after curing 24 h then continued curing to the target ages.

2.4. Testing methods

2.4.1. Mechanical properties testing

The 3 d, 7 d and 28 d were selected as the target ages. The compressive strength and flexural strength values of the prismatic sample were measured according to the ISO 679:2009 Cement-Test methods-Determination of strength. AWC-201 cement strength testing machine was used in this experiment. In our work, all the compressive strength and flexural strength values were the averages of three separate tests. Data that deviated more than 10% from the mean was eliminated. The tensile test of the dog-bone sample (28 d) was measured by universal testing machine according to ISO 6892-1-2016 Metallic materials. Tensile testing. Part 1: Method of test at room temperature. The loading speed was 0.4 mm/min.

2.4.2. SEM and BET test

The microstructure and morphology of the material were observed and analyzed by Hitachi S-4800. The Hitachi S-4800 is a field emission-scanning electron microscope (FE-SEM), capable of high resolution imaging and specimen topography study from nanometers to millimeters. The SEM samples were selected and cut from the original samples. The broken flakes were chosen

Table 1
Chemical composition of fly ash and steel slag/%

Chemical composition	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Fe_2O_3	K_2O	CaO	TiO_2	L.O.I.
Fly ash	0.45	0.85	22.4	40.7	0.71	2.17	5.34	0.69	9.46	1.16	16.1
Steel slag	0.20	10.3	9.78	21.9	1.32	0.61	14.9	0.29	37.4	1.03	2.27

Note: L.O.I is the Loss on ignition.