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High tensile strength fly ash based geopolymer composite using copper coated micro steel fiber

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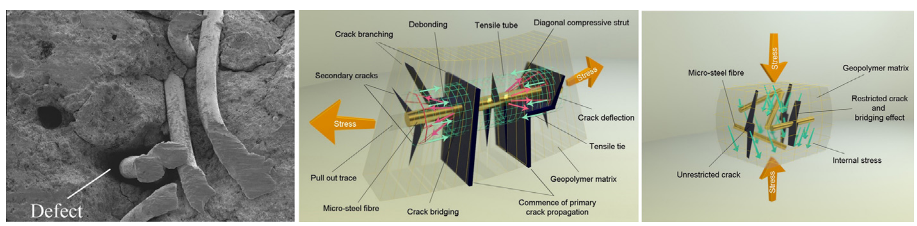
HIGHLIGHTS

- Incorporation of MSF controls the shrinkage of fly ash based geopolymer composite and minimizes it at 2% fiber content.
- The MSF geopolymer composites shows a significant improvement in flexural strength and energy absorption.
- Addition of MSF into geopolymer did not have an adverse effect on the compressive strength of the composite.

GRAPHICAL ABSTRACT



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ABSTRACT

As a ceramic-like material, geopolymers show a high quasi-brittle behavior and relatively low fracture energy. To overcome this, the addition of fibers to a brittle matrix is a well-known method to improve the flexural strength. Moreover, the success of the reinforcements is dependent on the fiber-matrix interaction. In this present study, effects of micro steel fibers (MSF) incorporation on mechanical properties of fly ash based geopolymer was investigated at different volume ratio of matrix. Various properties of the composite were compared in terms of fresh state by flow measurement and hardened state by variation of shrinkage over time to assess performance of the composites subjected to flexural and compressive load. The fiber-matrix interface, fiber surface and toughening mechanisms were assessed using field emission scan electron microscopy (FESEM) and atomic force microscopy (AFM) through a period of 56 days. Test results confirmed that MSF additions could significantly improve both ultimate flexural capacity and ductility of fly ash based geopolymer, especially at early ages without an adverse effect on ultimate compressive strength.

1. Introduction

Geopolymers are materials which are formed through the hydrothermal synthesis of aluminosilicate sources in the presence of alkali activators such as sodium hydroxide (NaOH) or sodium silicate (Na_2SiO_3) [1]. Due to the lower carbon dioxide emission, high early strength gain, durability against chemical attack, high surface hardness, and higher fire resistance, they have a great potential to be used in construction as an alternative to conventional Portland cement [2–7]. However, they suffer from quasi-brittle characters, deficiency of low flexural strength and sudden failure like most ceramics and Portland cement [8–10]. Furthermore, unlike Portland cement, water is not incorporated directly in synthesis of geopolymer gel [11]; instead, water is used to produce workable mixture and mediate the reaction [12,13]. Loss of such an extra water over time results in a large shrinkage on geopolymers specimens [14].

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Incorporation of fibers into brittle matrix is an efficient way to improve the flexural strength and enhance post peak characteristics due to controlling of crack propagation under different loading or environmental effects such as shrinkage [15,16]. Reinforcing of geopolymers was first investigated by Davidovits with the aim of fabricating molding tools and patterns for the plastics processing industry [17] and subsequently continued by other researchers with different type of fibers such as organic fiber like cotton fibers [8] and protein- based fibers [18], carbon fibers [16,19], steel fibers [15,20,21], PVA fibers [22] and polypropylene fibers [23] to overcome the brittleness and catastrophic failure of the composites.

In general, utilization of fibers is proposed to provide a control of cracking and to increase the fracture toughness of the brittle matrix leading to delay in sudden global failure of the composite. Debonding, sliding and fiber pull out are the local mechanisms that control the bridging action during both micro and macro cracking of the matrix. These mechanisms increase the demand of energy for crack propagation [16]. However the degree of improvement varies based on the type of fibers. In Portland cement based mixtures incorporation of steel fibers showed higher clamping pressure and friction than other types of fibers [24]. Similar results were obtained for geopolymers [20,25]. Steel fibers enhanced the load carrying capacity, cracking strength, rate of crack growth and crack width control of fiber reinforced geopolymer concrete [21]. The influence of fibers on flexural toughness and ductility improvement of geopolymers were reported to be higher than those of conventional Portland cement based composites [15,20].

Since the incorporation of large scale steel fibers in geopolymer matrices is limited due to extensive workability reduction, it is supposed that increasing the interaction surface of fiber and matrix by reducing the scale of fiber is an effective way to enhance the composite mechanical properties beyond the improvement of conventional fibers [26]. Recent findings have indicated that micro steel fibers (MSF) demand significantly high energy to pull out from ordinary Portland cements compared to that of other micro fibers such as polypropylene and polyvinyl alcohol fibers; this enhancement is because of a strong fiber-matrix interaction and high Young's modulus of the MSF [25,27].

In this study, the variation of the mechanical properties of MSF reinforced fly ash based geopolymer composites with respect to the amount of fibers in the matrix has been systemically investigated. It was observed that inclusion of MSF into fly ash based geopolymer matrix significantly reduced drying shrinkage and enhanced flexural strength and toughness without having negative influence on the ultimate compressive strength.

2. Materials characteristics and testing methods

2.1. Material characterization

The low calcium FA (class F) used in this research had been collected from Lafarge Malayan Cement Bhd, Malaysia with the major pozzolanic components of Silica (SiO_2) + Al_2O_3 (alumina) + ferric oxide (Fe_2O_3) = 95.5%, thus satisfying the requirements of ASTM: C618-12a. The oxide composition of the materials as determined by X-ray florescence (XRF) by PANalytical Axios mAX instrument is shown in Table 1. The particle size distribution test was measured by Mastersizers Malvern Instruments and the result is shown in Fig. 1; moreover, median particle size and specific gravity of the fly ash are 12.19 μm and 2.18.

The prepared MSF was about 22 mm in length, 0.2 mm diameter, 7.85 g/cm^3 density, tensile strength of ~2500 MPa and Young's modulus ~200 GPa and was expected to enhance the toughening mechanism and to control the shrinkage of the geopolymer matrix.

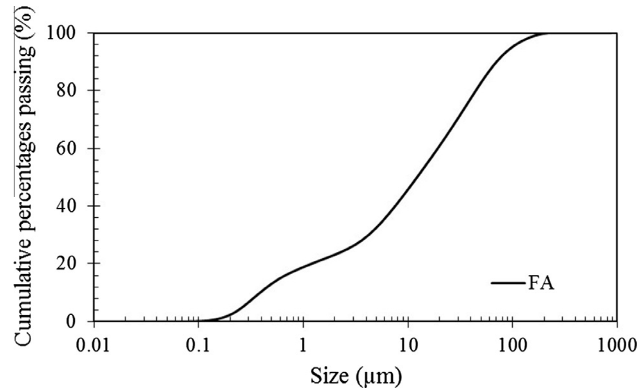

Fig. 1. Particle size distribution of the fly ash.

In this research a combination of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solutions was used as alkaline activator. NaOH was provided in the form of pellets with 99% purity while Na_2SiO_3 was used in liquid form with about 1.5 g water per milliliter at 20 °C with a SiO_2/Na_2O ratio of 2.5.

2.2. MSF fly ash based geopolymer composite preparation

The alkaline activator of this study was prepared by mixing 16 M NaOH with Na_2-SiO_3 and diluted with an extra water needed to increase the workability and uniformity of the geopolymer paste in order to get a mass ratio of Na_2SiO_3:NaOH:H_2O of 2.5:1.0:0.7. The alkaline activator was gradually added to the fly ash with the solution to solid ratio of 0.5 and mixed for 5 min with an automatic mixer. Afterward, MSF was added to the fresh geopolymer paste and mixed for another 3 min with the slow mixing rate, then immediately poured into stainless steel molds, sealed using cling film and cured in a 65 °C Memmert ULM600 oven for 24 h. After dismantling of the molds the specimens were kept in ambient condition with an average temperature and humidity of 32 °C and 65%, respectively until testing day. The MSF content of the geopolymer composites varied in the range of 0.5%, 1%, 2%, 3% and 4% of the volume. According to our preliminary casting, it was concluded that initial dry mixing of MSF/fly ash or MSF/alkaline activators resulted in accumulation of the fibers and agglomeration of matrix.

2.3. Flow measurement

The flow measurement was performed using truncated cone and shaking table method according to ASTM C1437-07 to evaluate the workability of the geopolymer matrix after incorporation of the MSF. The flow (F) resulted as an increase in average base diameter of the paste specimen (D), expressed as a percentage of the original based bottom diameter (D_0) by the following equation:

$$F = \left(\frac{D - D_0}{D_0}\right) \times 100$$

2.4. Shrinkage measurement

25 × 25 × 300 mm prisms were prepared to measure the shrinkage of the composites. After 24 h hot curing, the specimens were taken out from the oven and demec points fixed to the surfaces of the specimens using an epoxy adhesive. To measure the variation of shrinkage over time a Mitutoyo Absolute Digimatic Indicator ID-C112B apparatus was used with the range and resolution of 12.7 mm and 0.001 mm, respectively.

2.5. Density

Bulk density was measured by Archimedes method in accordance with ASTM C-20 after 60 days. The measurement was first done for suspended and saturated conditions and then for dried conditions. These sequences were suggested by the standard to avoid the effect of crack formation due to hot drying on density measurement. The saturated and suspended weight measured after 2 h boiling was followed by immersing specimens under distilled water in vacuumed condition for 24 more hours; to obtain the dry weight, the specimens were kept in an oven at 105 °C for 24 more hours to remove the water and obtain the dry weight.

Table 1
Chemical composition of fly ash.

Composition	SiO_2	Al_2O_3	Fe_2O_3	K_2O	TiO_2	CaO	SO_3	MgO	P_2O_5	Na_2O	ZrO_2	MnO
Fly ash (%)	75.76	15.86	3.90	1.14	0.97	0.95	0.35	0.26	0.21	0.16	0.13	0.06