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A feasibility study of strain hardening fiber reinforced fly ash-based geopolymer composites

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HIGHLIGHTS

- Strain-hardening ductile fly ash-based geopolymer composite was demonstrated.
- The tensile ductility of the composite could reach over 4%.
- Crack pattern analysis was conducted by Digital Image Correlation.
- The maximum and average crack widths are 117 and 45 μm, respectively, at 4.5% strain.

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ABSTRACT

Fly ash-based geopolymer has been intensively studied as a promising alternative to ordinary cement materials. While geopolymer concrete has good strength and excellent material greenness, applications have been limited to niche or small scale applications. In order to use geopolymer for large scale structural applications, the inherent brittleness should be addressed. In this study, strain-hardening ductile fiber reinforced geopolymer composites were developed by using randomly oriented short Poly-Vinyl Alcohol (PVA) fibers. Subsequently, their mechanical properties were investigated by cube compressive and dogbone tensile testing. Tensile strain hardening behavior with very high ductility of over 4% was experimentally demonstrated for the developed composites. These performances were found to be further improved by utilizing temperature curing methods. Crack width distributions were also investigated by using the Digital Image Correlation technique. The analysis indicated that the maximum and average crack widths are 117 μm and 45 μm, respectively, even at a high imposed strain level of 4.5%. Therefore, the feasibility of strain-hardening ductile geopolymer composites was established.

1. Introduction

The greenness potential of geopolymer, a promising alternative binder material to Ordinary Portland Cement (OPC), has so far not been fully realized in practice. Compared to cement manufacturing, which contributes 5–8% of the global emission of man-made CO_2, geopolymer production has 80% less carbon and 30% less energy footprints [1–3]. Moreover, industrial byproducts such as fly ash and slag can be utilized as source materials that are activated by alkaline solution to form geopolymer. Despite the outstanding environmental friendliness of geopolymer, however, use of geopolymer has to date been limited to niche applications or small scale products. To make the most of the excellent material greenness of geopolymer, large-scale applications in the construction industry should be seriously considered.

Over the last few decades, significant efforts have been made in the research community for understanding reaction mechanisms, chemistry and engineering properties of geopolymers. It has been found that fly ash-based geopolymer can exhibit better compressive strength and higher chemical, fire/temperature and frost resistance than OPC materials [4]. Geopolymer, however, is inherently brittle like conventional cement materials. Considering the large-scale applications, it is highly possible that the structural size effect resulting from material brittleness becomes significant. Further, as in OPC, a lack of structural durability will likely result if cracking in geopolymer is pervasive. Thus, a major step towards large-scale structural applications of geopolymer is to suppress its brittleness.

Fiber reinforcing has demonstrated to be highly effective in controlling the brittleness of cementitious materials. While fiber reinforced concrete (FRC) has enhanced fracture toughness, the

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Table 1
Mix proportion of fiber reinforced fly ash-based geopolymer.

Fly ash A	Fly ash B	Sand	Na_2SiO_3	NaOH (pellet)	Pre-mix water	Mix water	Fiber (vol.%)
0.8	0.2	0.3	0.256	0.056	0.039	0.12	2

Table 2
Chemical compositions and physical properties of fly ash.

	Fly ash A	Fly ash B
SiO_2	46.06–47.07	43.39–44.09
Al_2O_3	22.55–23.42	23.21–24.24
Fe_2O_3	17.69–19.03	7.98–8.39
CaO	3.55–3.91	13.22–14.04
SO_3	0.25–0.52	1.31–1.46
Loss on ignition	2.10–3.75	0.56–1.26
Fineness (% retained on 45 μm sieve)	13.80–15.00	16.85–19.13

material remains quasi-brittle. Over the last decades, the development of strain hardening cementitious composites (SHCC) has gained significant attention worldwide [5–7]. As example, Engineered Cementitious Composites (ECC), a micromechanics-based designed ultra-ductile SHCC, has demonstrated tensile strain capacity about 300% higher than plain concrete. Further, the self-controlled tight crack width contributes to improvement in durability due to lower permeability of water and chloride ions and better self-healing property even when damaged, as a result of crack width limited to below 60 μm. In addition, the deliberate choice of short fibers with moderate fiber volume fraction (less than 2%) in ECC is advantageous in field applications. These excellent properties have led to a number of full-scale applications of ECC in the building and transportation industries to date.

Previous research on fiber reinforcing geopolymer showed improvement in fracture toughness, tensile ductility and strength [8–13]. However, large fiber volume fractions or complicated processing methods such as extrusion are often employed, thus limiting the economics and field applicability of such geopolymer-based composites. While some studies demonstrated enhanced ductility using short fibers with moderate volume fractions, further improvement would be possible by utilizing the micromechanics-based design method originally developed for ECC. Lee et al. applied the micro-mechanical modeling concept to fiber reinforced alkali-activated slag mortar, and experimentally demonstrated the very high tensile ductility and tightly controlled crack width [14]. It is therefore hypothesized that the micromechanics-based design methodology holds promise to achieving ultra-ductile fiber reinforced geopolymer composites that can be placed in field conditions and provide improved structural durability.

The present paper reports a feasibility study of strain hardening fiber reinforced fly ash-based geopolymer composites with very high tensile ductility and tight crack width. Appropriate mix proportions are determined through experiments, utilizing knowledge obtained from ECC development. Mechanical tests are then conducted to characterize the compressive and tensile strength, tensile behavior, and tensile strain capacity. In addition, the tensile crack pattern is investigated by Digital Image Correlation (DIC) technique, providing information on the number of cracks and crack width distribution over a given gage length at any strain level under load.

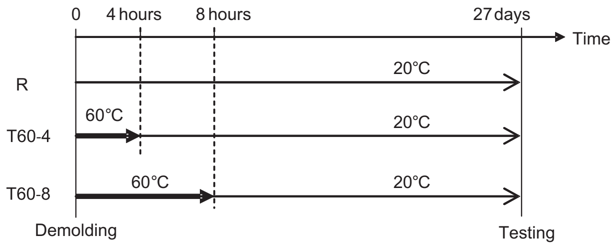

Fig. 1. Demolding 24 h after casting.

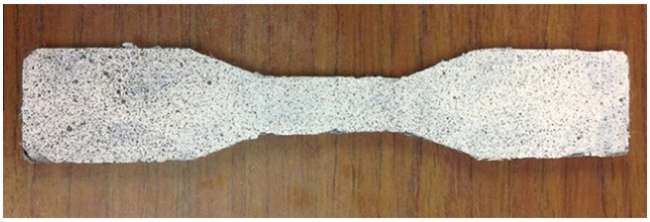

Fig. 2. Random speckle patterns make unique gray scale distributions in each specimen subset.

2. Experimental investigation

2.1. Materials and mix proportions

The mix proportion of geopolymer mortar was first determined through trial mixing so that the mortar has good mechanical properties, moderate setting time and adequate rheology for fiber dispersion. Poly-Vinyl Alcohol (PVA) fibers were employed with a volume fraction of 2%. Table 1 lists the resultant mix proportion of the geopolymer composite. The ratio is in terms of weight of the ingredients, except for the fiber that is expressed in terms of volume fraction. Two types of fly ash were used in this study, labeled Fly ash A and B, respectively. Fly ash A was obtained from Headwaters Resources and Fly ash B from Lafarge. Both are classified as class F fly ash as designated by ASTM C 618. Table 2 lists the chemical compositions and physical properties of fly ashes reported from each manufacturer. Slight variation is found in the reported data depending on the report date.

The purpose of using two types of fly ash is to control the hardening property of geopolymer mortar. When the fly ash A is singly used as the reactant, the specimens did not stiffen enough and fractured in demolding one day after casting. On the other hand, the use of fly ash B by itself resulted in too fast setting time to cast in molds. These problems might be related to the different amount of CaO content between Fly ash A and B, but further investigation would be required.

The alkaline activator consists of sodium silicate solution with 8.9 wt% Na_2O, 28.7 wt% SiO_2, and 62.5 wt% H_2O, laboratory-grade sodium hydroxide in pellet forms, and pre-mix tap water. Sodium silicate solution and pre-mix water were first mixed, and sodium hydroxide pellets were then dissolved in the solution. The solution preparation was done 24 h before its use as activator for geopolymer, as recommended in the research community, so that chemical equilibrium is attained. Additional water (labeled "Mix water" in Table 1) was used when mixed with solid materials (fly ash, silica sand and fiber) to obtain adequate rheology. As in most ECC materials, fine silica sand with an average diameter of 110 μm was used as aggregate and PVA fibers with 1.2% oil coating by weight were employed. Fiber properties are listed in Table 3.

Table 3
Properties of PVA fiber.

Fiber type	Nominal strength (MPa)	Apparent strength[a] (MPa)	Diameter (μm)	Length (mm)	Young's modulus (GPa)	Elongation (%)
REC 15	1620	1092	39	12	42.8	6.0

[a] Strength of fibers embedded in a cement matrix is lower than that in standard fiber strength testing.