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Tensile behavior and microstructure of hybrid fiber ambient cured one-part engineered geopolymer composites

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HIGHLIGHTS

- One-part geopolymer system was improved for ambient cured in-situ applications.
- Different hybrid fiber combinations were implemented to reinforced one-part geopolymer.
- The mechanical performances of hybrid fiber reinforced one-part geopolymer paste and mortar were established.
- Hybrid combinations performed better in slag geopolymer system compared to blended system (50% fly ash and 50% slag).

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ABSTRACT

This paper investigates the tensile behavior of the recently developed ambient-cured one-part engineered geopolymer composites (EGC) incorporating different hybrid combinations of steel (ST) and polyethylene (PE) fibers while maintaining the total fiber volume at 2%. Two ambient-cured geopolymer matrices were manufactured: the first was synthesized by activating slag (100%) while the second was a blended of 50% fly ash and 50% slag. The effects of using different precursor materials and hybridization content on the matrix and composite properties of EGC including workability, density, compressive strength, matrix fracture properties (elastic modulus, fracture toughness and crack tip toughness), tensile response and matrix microstructure were evaluated. The effect of 212 μm sand addition on the matrix and composite properties of the hybrid composite 1.5% PE and 0.5% ST was also assessed. It was found that the slag based EGCs exhibited a relatively better tensile response (i.e. strain hardening and multiple cracking behaviors) compared to the blended EGC composites although they achieved a comparable compressive strength. SEM observations revealed that the slag geopolymer matrix was relatively denser and more compacted compared to the blended geopolymer matrix. The sand addition impaired the strain hardening and multiple cracking behaviors of both slag and blended EGC yet increased the compressive strength and enhanced the fracture properties of the geopolymer matrices.

1. Introduction

Concrete is the highest demanded material worldwide for construction. The rapid increase in concrete consumption is attributed to infrastructure development and population growth [1]. The production of one ton of concrete emits around 0.85 to one ton of carbon dioxide (CO_2) [2]. In addition, researches have shown that the concrete production is responsible for 5–7% of total CO_2 emission into the atmosphere yearly, which is one of the greenhouse gases causing global warming [1–3]. Thus, it is indispensable to replace cement (partially or fully) with other environmentally friendly materials with low carbon footprint to maintain sustainability. Cementless concrete which is also referred to geopolymer concrete was proposed by Davidovits [4]. The CO_2 emissions during the production of geopolymer concrete are 50–80% less compared to ordinary concrete and approximately 60% less energy is required [5]. Geopolymer concrete is produced by polymerization of natural aluminosilicate materials such as metakaolin or industrial byproducts like fly ash or slag using high alkaline solutions [6]. Substantial researches have been conducted on geopolymer concrete to understand its microstructure, durability and structural behavior [7,8]. The first implementation of geopolymer concrete in structural application was the University of Queensland's Global Change Institute building in 2013 [9], followed by Brisbane West Wellcamp airport in 2014 [10]. However, geopolymer concrete is still a highly brittle material even though it is environmentally friendly.

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Notations

The following symbols are used in this paper:

E_m	matrix elastic modulus;
f_{cu}	composite compressive strength;
f_{cum}	composite compressive strength;
J_{tip}	matrix crack tip toughness;
k_m	matrix fracture toughness;
n	number of cracks;
S	average crack spacing;
r	density of composite;
r_m	density of matrix;
s_{fc}	=first cracking strength;
s_{cu}	ultimate tensile strength;
εcu	stain at ultimate load; and
Γp	relative slump.

The use of continuous aligned fibers [11] and randomly oriented short fibers [12] has gained an enormous interest in research during the past decades to enhance the brittle tensile behavior of cementitious materials. The term "high-performance fiber-reinforced cementitious composite" (HPFRCC) was introduced by Naaman [13]. Generally, HPFRCCs have a fiber content of 4–20% resulting in tensile strain capacity of 1% [14]. A special class of HPFRCCs called engineered cementitious composites (ECC) with fiber content of 2% typically has been developed which revealed a relatively high tensile ductility up to 8% [15,16]. Recently, many researches have been conducted on the strain hardening engineered cementitious composites (ECC) to understand the material behavior and its implementations in structural use [17–19]. Then, the concept of hybridization started to get notice in research area which is the idea of combining two or more fibers with different properties to attain a composite that holds the benefits from each fiber type [20,21]. The implementations of hybrid ECCs in structural use were also studied by many researchers [22]. However, ECCs contain high amount of Portland cement (2–3 times) compared to the conventional concrete which resulted in detrimental higher heat of hydration and cost [23,24]. Accordingly, the high cement content in ECCs will affect its sustainability performance due to the high embodied energy and CO_2 emissions companioned with cement production. Thus, a new green ECC material has been developed recently by fully replacing the Portland cement with geopolymer cement, to form Engineered Geopolymer Composites (EGC).

2. Engineered geopolymer composites (EGC)

The research area of fiber reinforced geopolymer composites (FRGC) is still relatively new [25]. Limited researches were conducted on extruded FRGC [26,27]. Additionally, two feasibility studies were carried out on slag-based EGC [28] and fly ash-based EGC [29] wherein both exhibited tensile strain hardening behavior.

Fly ash-based FRGC incorporating different types of mono fibers were previously tested such as basalt fibers [30], carbon [31], cotton [32], glass [33], natural flax [34], polypropylene [35], Polyvinyl alcohol (PVA) [36] and steel [37]. On the other hand, Shaikh [38] studied the deflection hardening behavior of fly ash-based FRGC using hybrid fiber combination of steel and PVA. Several factors affecting the mechanical behavior and microstructure of fly ash-based FRGC were also studied such as type of activator [39], duration of heat curing and rest period (i.e. before heat curing) [40], modulus ratio of activator [41], water content (water to geopolymer solids ratio W/GP) [42] and sand addition [43]. Other researches focused on slag-based FRGC reinforced with polyethylene (PE) fibers [44]. Furthermore, Nematollahi et al. [45] studied the tensile behavior of blended (50% FA and 50% slag) FRGC incorporating PE and PVA fibers.

However, the use of hostile, corrosive and viscous alkali solutions to synthesize conventional two-part geopolymer confines the in-situ applications of such materials. Thus, a new class of geopolymer composites was developed and called "one-part" or "just add water" geopolymer [46,47]. One of the challenging issues of producing the conventional two-part geopolymer is the need to handle a large amount of user hostile chemical solutions [45]. While the production of one-part geopolymer requires a small amount of solid activators which is considered to be more economic and feasible.

This paper aims to comprehend the mechanical behavior of hybrid fiber one-part EGC before permitting the structural use of such material, with the intention of combining the advantages of ECC, Geopolymer as well as the hybrid use of fibers. In this research, different hybrid combinations of ST and PE fibers are studied while maintaining the total fiber volume fraction (V_f) of 2%. Further, the impact of using different precursor materials like FA and GGBFS on synthesizing EGC and the effect of sand addition on the tensile strain hardening behavior of the hybrid composites are evaluated.

3. Materials

3.1. Fly ash and slag

Two precursor materials were used in this study to synthesize EGC specimens including low calcium class F fly ash (FA) produced in Hong Kong and ground granulated blast furnace slag powder (GGBFS) produced in China. Table 1 reports the chemical compositions of both fly ash and GGBFS which were determined by X-ray Fluorescence (XRF) test. Scanning electron microscope (SEM) test was used to observe the morphology of fly ash and GGBFS particles. As shown in Fig. 1, the anomalous shape of GGBFS particles was predominant whereas FA particles were mainly solid spheres. Fig. 2 shows the X-ray Diffraction (XRD) patterns of fly ash and GGBFS raw materials. Clearly, the GGBFS contains more amorphous contents relative to the FA; which means that the GGBFS was more reactive compared to the FA. In other words, the rela-

Table 1
Chemical composition of fly ash and slag determined by XRF.

chemical	Results (% by weight)	
	Fly ash	GGBFS
SiO_2	44.4	18.9
Al_2O_3	32.6	6.43
CaO	6.67	66.9
Fe_2O_3	6.49	0.74
MgO	1.86	1.41
SO_3	2.27	1.97
TiO_2	1.24	1.88
K_2O	1.81	0.67
P_2O_5	0.44	0.08
SrO	0.14	0.18
LOI[a]	3.76	0.25

[a] Loss on ignition.