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Tensile Behavior of Hybrid Steel-Polyethylene Reinforced Slag-Based One-Part Engineered Geopolymer Composites

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ABSTRACT

This paper reports the results of an experimental investigation conducted on the tensile behavior of Hybrid Fiber Engineered Geopolymer Composites (HF-EGC) synthesized by the alkali activation of slag. The hybridization was achieved by combining different volume fractions of steel (ST) and polyethylene (PE) fibers, while maintaining the total fiber volume fraction at 2%. The tensile response including strain hardening and multiple cracking behaviors of HF-EGC was evaluated. The workability and compressive strength of all EGCs were also assessed. It was found that the workability and compressive strength of all EGCs increased when increasing the ST volume fraction included in the hybrid composite. All slag based HF-EGC exhibited tensile strain hardening behavior with multiple cracks where the hybridization showed no significant effect on the ultimate tensile strength of the composites. However, the ST volume fraction was related to the first cracking tensile strength while the PE volume fraction was directly related to the strain capacity of the composite.

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INTRODUCTION

Concrete is a highly demanded material in construction sector worldwide. However, the production of one ton of concrete emits one ton of carbon dioxide (CO_2) which is considered one of the greenhouse gases that causes global warming and affects the ozone layer. Davidovits (1991) proposed a new type of Cementless green concrete named geopolymer concrete.

The concept of using discrete fibers to reinforce brittle materials is not new. The application of Fiber reinforced concrete (FRC) in the concrete industry prospered in the early 1960s (Naaman, 1985). In general, the using of fibrous materials in concrete significantly improved the tensile response, cracking behavior and durability of the concrete. Recently, new class of cementitious composites named engineered cementitious composites (ECC) was developed which could exhibit strain hardening behavior with up to 8% ductility (Yu et al., 2018). Several researches were conducted on ECC reinforced with mono and hybrid fiber combinations (Ahmed and Maalej, 2008).

However, the cement content of ECC is 2 to 3 times that of the conventional concrete which resulted in detrimental higher heat of hydration and cost (Yang et al., 2007). Accordingly, the sustainability performance of ECC will drop because of the high embodied energy and CO_2 emissions companioned with cement production. Thus, a new green ECC material was developed recently called Engineered Geopolymer Composites (EGC) by substituting the Portland cement with geopolymer cement.

The goal of this paper is to understand the mechanical behavior of hybrid steel-polyethylene reinforced slag-based one-part EGC in order to permit the structural use of such material. In this research, different hybrid combinations of steel (ST) and polyethylene (PE) fibers are studied while keeping the total fiber volume fraction (V_f) at 2%.

Experimental Program

The tensile behavior was evaluated by testing dog bone shape specimens in accordance with the Japan Society of Civil Engineers (JSCE, 2008). The dimensions of typical dog bone specimen and the test setup are shown in Fig 1. Three dog bone specimens and three 50 mm cubes were cast for each hybrid combination. Table 1 shows the mix proportions and the hybrid combinations achieved in this study. The total volume of fibers was fixed at 2% in all mixes.

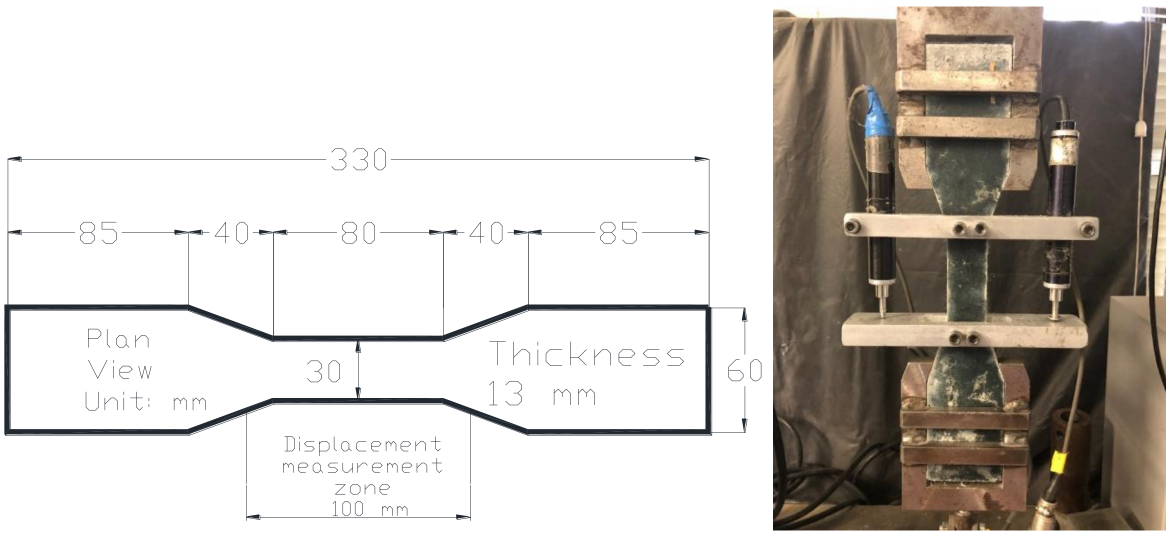


Fig. 1. Test setup and dog bone specimen details

Materials

Ground granulated blast furnace slag powder (GGBFS) locally produced in China was used as aluminosilicate precursor material in this study. Straight steel fiber and ultra-high molecular weight polyethylene fibers were used in this study. The properties of steel and PE fibers as provided by the manufacturers are shown in Table 2. The activator used in this study was anhydrous sodium metasilicate powder with 50.46% and 47.24% of Na_2O and SiO_2 by weight respectively. The used of solid powder as an activator is referred to "just add water" or "one-part" geopolymer (Luukkonen et al., 2017).

All specimens including their companion cubes were cast from a single patch. All mixes were prepared in Hobart mixer. After casting, all specimens were compacted used mechanical vibrator. All specimens were covered with wet burlap and plastic sheets for 24 hours. After that, the curing was continued and the specimens were kept in water tank for the next 27 days till testing day. All the tests were conducted when the EGC reached 28 days of age.

Table 1. Experimental program and mix proportions

Specimen	**Fiber volume fractions (%)**		**Binder**	**Activator/ Binder**	**Water/ Binder**
	PE	ST	Slag		
P:EGC-S	2.0%	0.0%	1	0.12	0.45
	1.5%	0.5%			
	1.0%	1.0%			
	0.5%	1.5%			
	0.0%	2.0%			

Table 2. Properties of fibers

Fiber type	Length (mm)	Diameter (μm)	Modulus of elasticity (GPa)	Strength (MPa)	Density (g/cm^3)
ST	13	180	200	2850	7.8
PE	13	17	114	3000	0.97

Instrumentations and testing

The tensile response of HF-EGC was evaluated through uniaxial direct tension test performed in accordance with the Japan Society of Civil Engineers (JSCE, 2008). The test was conducted using universal testing machine with extension control rate of 0.5 mm per minute as mentioned in JSCE. The deformations were measured over a gauge length of 100 mm using two LVDTs as shown in Fig. 1. The 50 mm cube specimens were tested in accordance with ASTM C109.

Mini slump test (flow table test) was conducted in accordance with ASTM C1437-15 to test the workability of all HF-EGC composites. The following equation (Nematollahi and Sanjayan, 2014) was used to report the relative slump values:

$$\Gamma_P = (\frac{d}{d_o})^2 - 1 \quad ..... (1)$$

where $\mathbf{\Gamma}_p$ is the relative slump, *d* is the average of 3 measured diameters of the spread and d_o is the cone bottom diameter which equals to 100 mm as stated in ASTM C1437-15. All the slump tests were conducted after 15 to 20 minutes of water addition to the HF-EGC mixes.

Test Results

Fig. 2 shows the relationship between relative slump results and the hybrid combinations of ST and PE. It was found that the fiber addition adversely affected the flowability (workability) of the one-part EGC matrix (without fibers). Such adverse effect of fiber addition on flowability was more pronounced in case of including more PE fibers in the composite. In other words, the workability of HF-EGC composites is decreased by increasing the PE fiber content in the hybrid composites. The relative slump of the EGC matrix (without fibers) was 4.02 while the relative slump of the HF-EGC composites ranged from 1.42 to 3.65 depending on the hybrid combination.

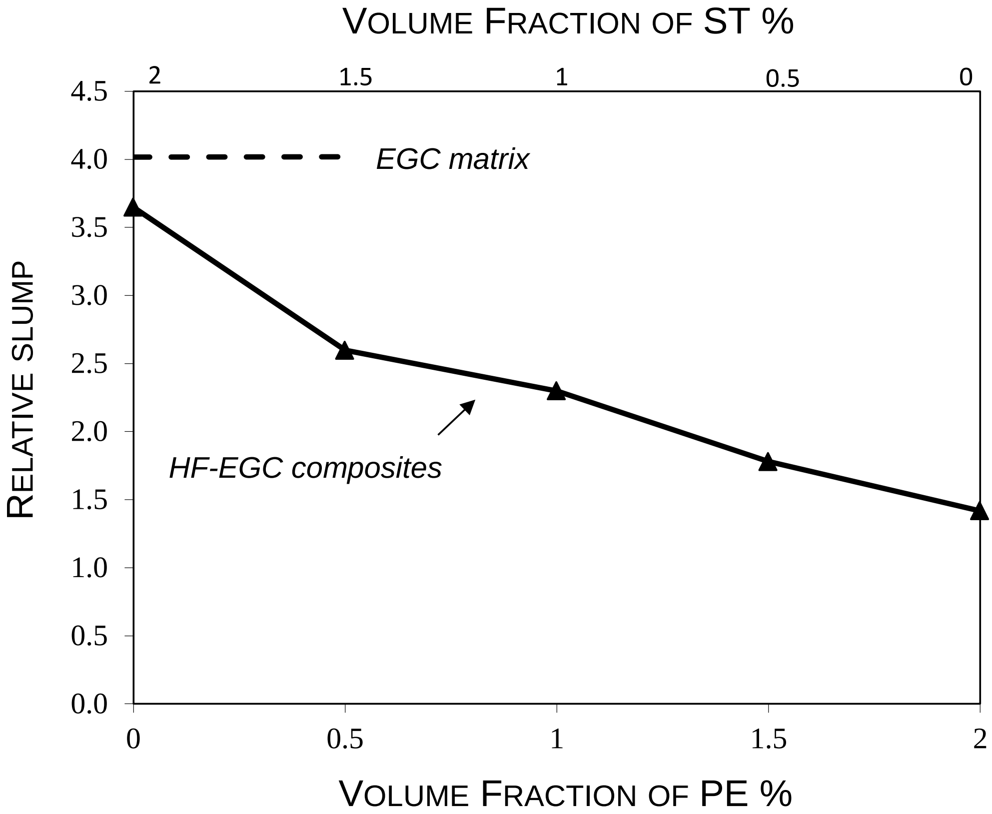


Fig. 2. Relationship between relative slump and PE & ST volume fraction

Fig. 3 plots the relationship between the compressive strength and different hybrid combinations of PE and ST. It was found that the fiber addition enhanced the compressive strength of the one-part EGC matrix regardless to the fiber type. Further, it was noticed that including more ST fibers in the HF-EGC composite improved its compressive strength relative to EGC matrix. Similar observation was reported by previous researches (Alrefaei et al., 2017). The average compressive strength of the EGC matrix (without fibers) was 59 MPa while the average compressive strength of the HF-EGC composites ranged from 63 (mono PE composite) to 77 MPa (mono ST composite) depending on the hybrid combination.

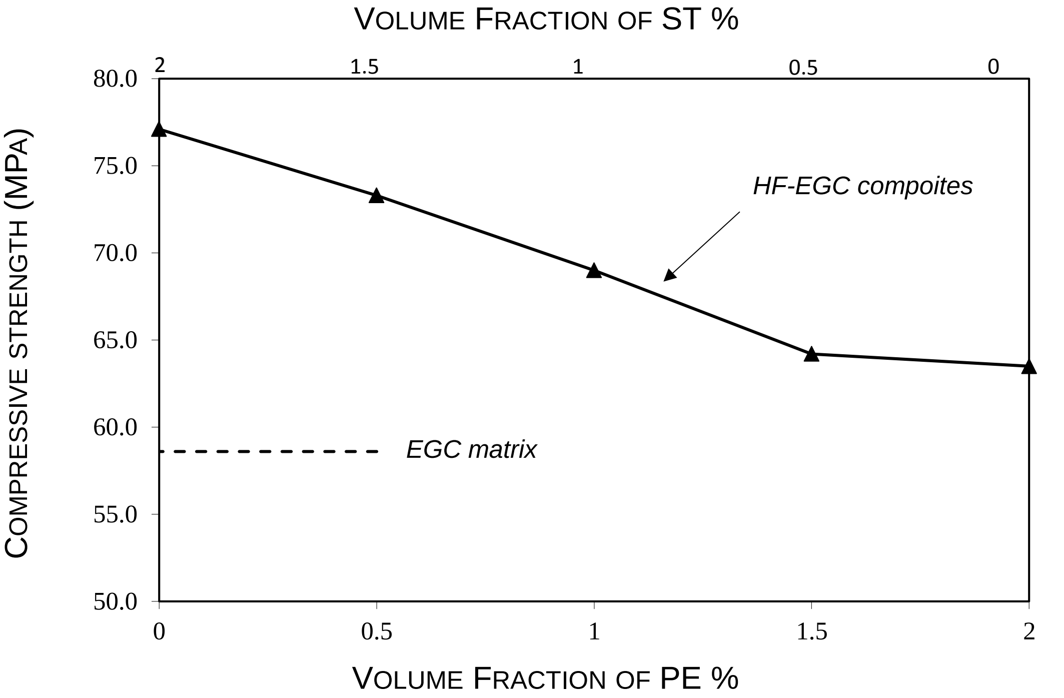


Fig. 3. Relationship between compressive strength and PE & ST volume fraction

Fig. 4 plots the tensile responses of all HF-EGC composites achieved in this study. As shown in Fig. 4, the hybrid composites responses lie between the envelop of mono ST and mono PE composites. This phenomenon is similar to that reported by Ahmed and Maalej (2009). The HF-EGC composites including higher PE volume fractions exhibited a relatively higher strain hardening behavior relative to mono ST composite. Thus, the tensile strain capacity of the composite was directly related to the PE volume fraction included in the EGC. One the other hand, the cracking strength of the HF-EGC composites was dependent on the ST volume fraction included in the EGC. In other words, the higher the ST volume fraction added to the HF-EGC, the higher the first cracking strength will be. Regarding the ultimate tensile strength, the mono ST composite achieved 4.16 MPa which was the highest value among the HF-EGC. However, the hybridization showed no significant effect on the ultimate tensile strength of HF-EGC composites since the ultimate strength ranged from 3.25 to 3.43 MPa.

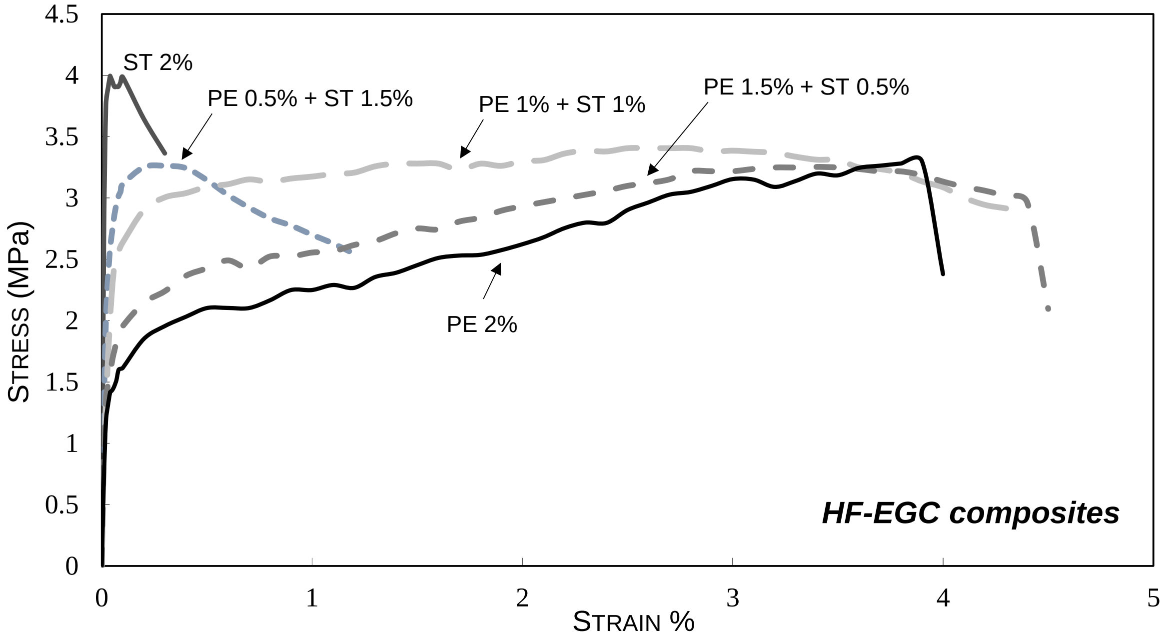
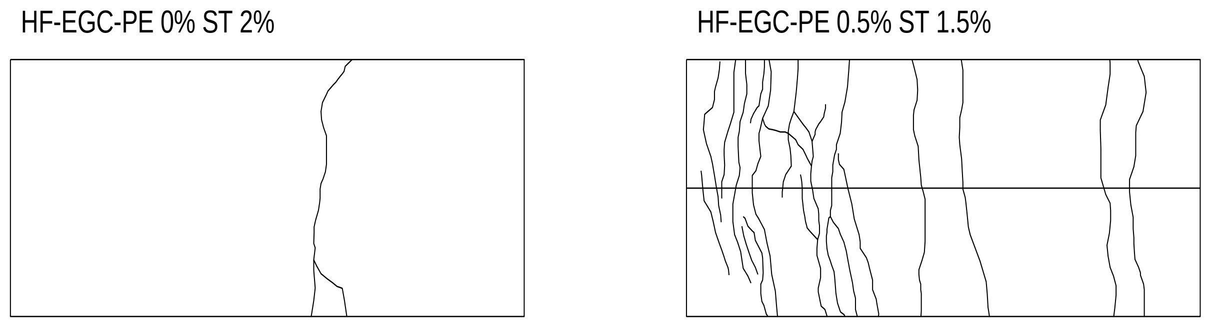


Fig. 4. Tensile responses of HF-EGC composites

Fig. 5 shows the cracking behavior of the HF-EGC composites. The mono ST composite showed a typical tensile failure with one major crack. The HF-EGC composites showed a high level of multiple cracking behavior, especially in case of using relatively high percentage of PE fibers. Similar observations were reported by previous researches (Ahmed and Maalej, 2009; Alrefaei et al., 2017). Moreover, the multiple cracking behavior led to a high strain capacity in the HF-EGC containing a relatively large amount of PE fibers as discussed previously.



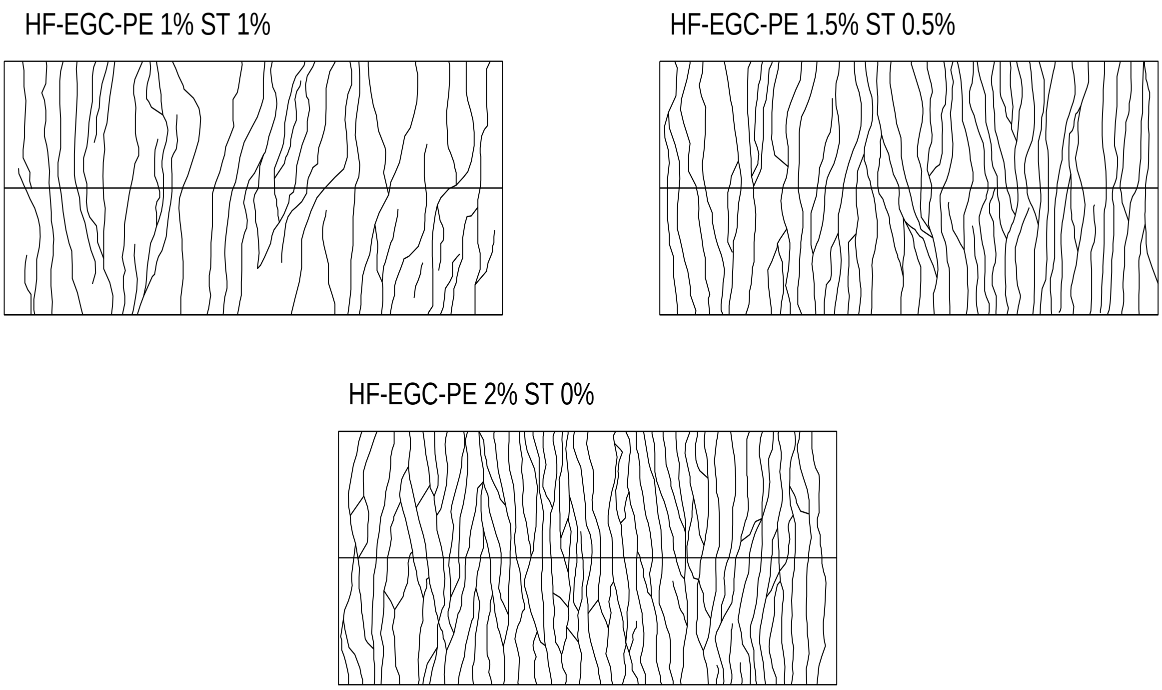


Fig. 5. Multiple cracking behavior of HF-EGC composites

Conclusions

This paper evaluated the tensile behavior of hybrid fiber slag-based one-part engineered geopolymer composites (HF-EGC) with a total fiber volume fraction of 2%. It was found that all HF-EGC composites exhibited tensile strain hardening behavior with multiple cracks. The ultimate tensile strength of the HF-EGC composites was not affected by the hybridization process regardless mono ST composite. The ST volume fraction was related to the first cracking tensile strength while the PE volume fraction was directly related to the strain capacity of the composite. Further, it was found that increasing the ST volume fraction in the HF-EGC composite improved both workability and compressive strength.

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