Mechanical properties of steel fibre reinforced geopolymer composites cured under ambient temperature

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ABSTRACT

Geopolymers represent the most promising green alternative to ordinary Portland cement and cementitious materials. In case of cement free (geopolymer) concrete, heat curing is essential to provide sufficient mechanical properties in early curing stages. However, there are several practical issues with the application of heat curing in large scale structures.

The main aim of the current study is to develop steel fibre reinforced geopolymer concrete (SFRGC) with high mechanical performance without the need for heat curing treatment. Extensive experimental work has been conducted in order to optimize the mix design of fibre reinforced geopolymer concrete. In the examined mixes, different steel fibre lengths and volume fractions have been used, and the specimens have been cured under ambient temperature.

Compressive, and direct tensile tests have been conducted to evaluate the mechanical properties of the examined mixes. Scanning electronic microscopy (SEM) has been used for microstructural analysis. The experimental results show that addition of steel fibre considerably improved the post cracking behavior of the material under tension, and based on the tensile testing results, as fibre volume and aspect ratio were increased the ultimate strength were significantly improved.

Keywords: Geopolymer, Ambient curing, Fly Ash, Slag, Silica Fume, Steel Fibre

1. Introduction

Fibre Reinforced Cementitious Composites (FRCCs) have been developed, and extensively researched, over the last two decades (Shaikh, 2013). It has been reported that FRCCs significantly contribute to the enhancement of the service life of civil infrastructure due to fibres'-bridging action across the cracks. FRCCs mixture require higher contents of cement than normal concrete in order to increase interfacial bond strength and to account for the absence of coarse aggregates in the mix design (Choi et al., 2012). High cement content however introduces heat of hydration, higher shrinkage and increased cost (Altwair et al., 2012).

Geopolymers represent the most promising green and eco-friendly alternative to ordinary Portland cement and cementitious materials. Geopolymer concrete is a relatively new material based on industrial by-products such as fly Ash, slag, metakoline, rice husk ash and silica fume. The adoption of geopolymer materials could reduce the carbon dioxide emissions associated with the manufacturing of cement by up to 80% (Lee and Lee, 2013). Geopolymer (cement-less) materials can play an important role in the context of sustainability and environmental issues while at the same time geopolymer materials can also have enhanced mechanical properties and durability. Their relatively poor tensile and bending strengths compared to conventional Portland Cement this drawback could be overcomed by the addition of micro fibre additives (Natali et al., 2011). Aydın and Baradan (Aydın and Baradan, 2013) examined the effect of steel fibres on the mechanical properties and on the drying shrinkage of alkali activated slag and silica fume mortar. The results show that incorporation of steel fibres led to improved flexural toughness and reduced drying shrinkage strain.

The performance of fibre reinforced composites depends on the properties of the matrix and the fibres (Aydın and Baradan, 2013). Bernal et al., (Bernal et al., 2010) evaluated the mechanical and permeability properties of Alkali Activated Slag Concrete (AASC) reinforced with steel fibres. The experimental results indicated that AASC reinforced with steel fibres exhibits better mechanical performance than

Ordinary Portland Cement (OPC) concrete. Natali et al., (Natali et al., 2011) investigated the effect of different fibre types on the flexural performance on fibre reinforced geopolymer composite (Carbon, E-glass, Polyvinyl Alcohol (PVA) and Polyvinyl Chloride (PVC)). Their experimental results showed that application of all fibre types significantly improved the flexural strength and post-crack ductility.

Regarding the curing conditions, and based on previous studies (Davidovits, 2011, Deb et al., 2014, Islam et al., 2014), fly ash based geopolymer concretes require high temperatures treatment in order to obtain comparable performance (mechanical, physical and durability properties) to conventional concrete. However, heat curing treatment leads to increased cost and practical issues preventing in situ application of geopolymer concrete at large scale and to date there are very limited published studies on geopolymer concrete cured under ambient temperature (Deb et al., 2014, Nath and Sarker, 2014, Lee and Lee, 2013).

Previous experimental investigation conducted by the authors has focused on the evaluation of the performance of various geopolymer mixes cured under ambient temperatures (Mohammed Al-Majidi, 2016). The geopolymer matrix assessed in this study was produced using geopolymer binder (fly ash, slag and silica fume) mixed with potassium silicate alkaline activator. The main aim of the current study is to investigate the enhancement of the mechanical properties of geopolymer concrete cured under ambient temperature, by the addition of steel fibres. The effect of fibre lengths and volume fractions on the mechanical properties of the geopolymer materials has been evaluated through compressive strength, and tensile strength tests. In addition, the microstructural properties of the examined mixes were examined using Scanning Electron Microscopy (SEM).

2 Materials and experimental procedure

2.1 Materials and mix proportions

The geopolymer mortar matrix adopted in the present work was based on geopolymer binder (fly ash, slag and silica fume) mixed with potassium silicate with molar ratio equal to 1.25 and fine aggregate (Mohammed Al-Majidi, 2016). Silica sand with a particle size less than 0.5 mm was used as fine aggregate. The chemical compositions of the fly ash, slag and silica sand used are presented in table 1. Total binder and silica sand quantities of 775 kg/m3 and 1054 kg/m3 respectively were used for the mixes of the current investigation, values based on a previous study.

Table 1. Chemical compositions of FA, GGBS and Silica Sand.

Chemical compositions (%)	Fly ash	Slag	Silica Sand
Silicon Dioxide, SiO_2	59	35	99.73
Aluminum Oxide, Al_2O_3	23	12	0.1
Calcium Oxide, CaO	2.38	40	--
Ferric Oxide, Fe_2O_3	8.8	0.2	0.051
Sulphur Trioxide, SO_3	0.27	--	--
Sodium Oxide, Na_2O	0.74	--	<0.05
Potassium Oxide, K_2O)	2.81	--	0.01
Magnesium Oxide, MgO	1.39	10	--
Loss on ignition, LOI	6.7	--	0.09

Six different mixtures were prepared, with varying fibre volume fractions (2% and 3%) and aspect ratios (37.5% and 81.5%). Steel fibres were sourced from Dramix, with lengths of 6mm and 13mm and diameter 0.16mm (Fig.1).

A Zyklos 75L mixer (Pan Mixer ZZ 75 HE) was used to prepare the fibre reinforced geopolymer composite. Geopolymer binder (Silica fume, fly ash and slag) placed first in the mixing drum, followed by alkaline liquid, and sand. The materials were dry mixed for 5 min before adding the water and alkaline activator. Mixing continued for a further 4 min before the fibres were added, followed by silica sand, to give a total mixing time of 13 minutes.

Fig. 1. Steel fibres used in this study

Table 2. Mixture compositions of steel fibre reinforced geopolymer mortar used in the present study.

Mix ID	Fly Ash/ Binder	Slag / Binder	Silica fume/ Binder	K_2SiO_3/ Binder	Water/ Binder	Steel fibre aspect ratio (L/D)	Steel fibre volume fraction
PG	50%	40%	10%	12%	25%	0	0%
2St6	50%	40%	10%	12%	25%	37.5	2%
3St6	50%	40%	10%	12%	25%	37.5	3%
2St13	50%	40%	10%	12%	25%	81.25	2%
3St13	50%	40%	10%	12%	25%	81.25	3%
3hyb St (6+13)	50%	40%	10%	12%	25%	50% 37.5 +50% (81.25)	3%

2.2. Experimental equipment and test procedures

Compressive and direct tensile strength tests were conducted to determine the mechanical properties of the examined mixes. Compressive strength values were determined at 28 days using four cubes with 100mm side for each mixture. Tests were conducted under constant loading rate of 180 KN/min [13]. Direct tensile was determined using ‘dog bone’ shape specimens with mid-cross section dimensions 13mm X 50 mm (fig. 2a). The average extension was measured using Linear Variable displacement Transducers (LVDT) attached to a steel frame as shown in fig.2b. Direct tensile tests were conducted under displacement control with a constant rate of 0.4mm/min.

The microstructure of the mixtures was examined using Scanning Electronic Microscopy (SEM). Plain Geopolymer and SFRGC samples were taken from the cracked specimens after the end of the tensile tests. Samples were coated with carbon and imaged using a Leo S420 stereoscan scanning electron microscope with an accelerating voltage range of 1-30 kV.

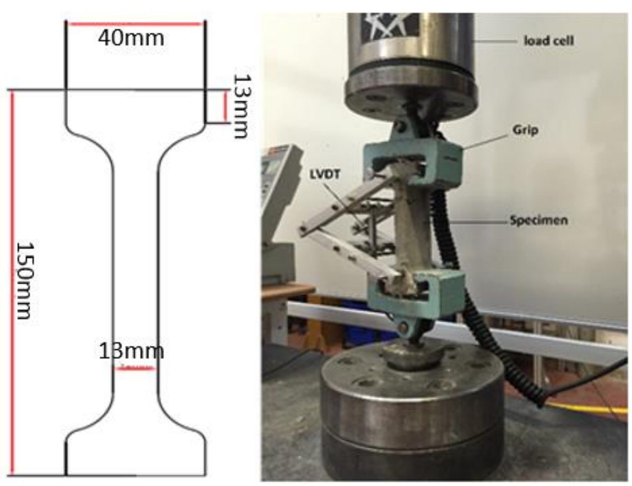


Fig. 2. Experimental set up for (left) dog bone specimens and (right) tensile strength test set up

3. Results

3.1 Compressive strength

The average compressive strength results alongside with the scatter of the results for plain and steel fibre reinforced geopolymer composites are presented in Fig. 3.

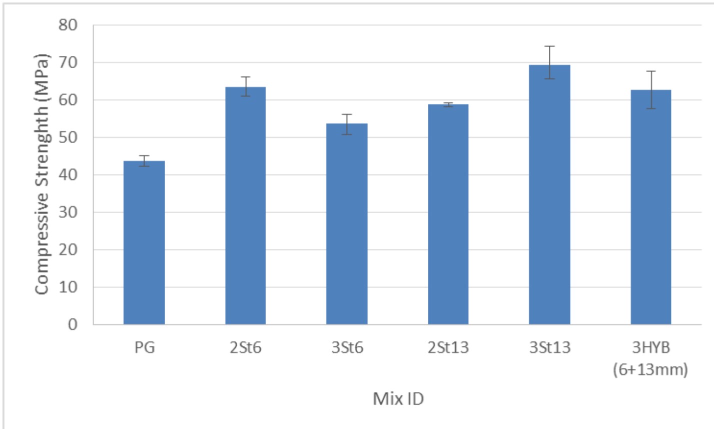


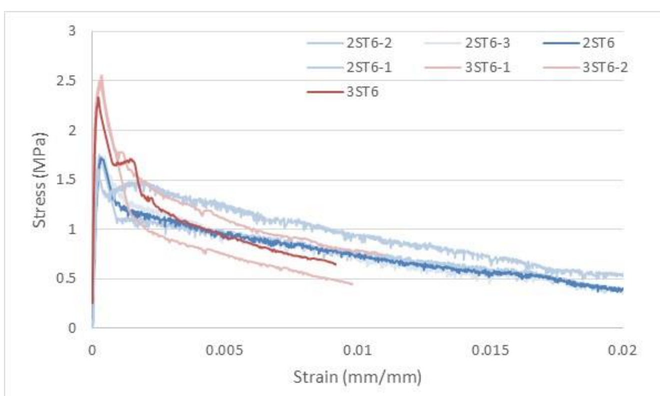
Fig. 3. Compressive strength of steel fibre reinforced geopolymer composite (SFRGC)

The average compressive strength of the plain geopolymer mortar was 43.7 MPa. The incorporation of steel fibres increased the average compressive strength values by 15-25 MPa depending on the fibre length and dosage rates. Increment of the aspect ratio and volume fraction of the reinforcing steel fibres did not lead to a systematic increase in compressive strength performance. The compressive strength of 3% St13 showed the highest value of around 70 MPa. The results of figure 3 indicate that in all the examined cases, there is an increment of the compressive strength by the addition of steel fibres, although there is no clear relationship between the increase in compressive strength and the aspect ratio or volume fraction of the steel fibres used.

3.2 Tensile Strength test

Direct tensile tests were carried out in order to investigate the effect of steel fibre aspect ratio and volume friction on the tensile strength of the examined mixes. Fig.4 shows the average direct tensile stress–strain together with the individual results for all the examined specimens.

Fig 4a. Tensile stress-strain response of SFRGC -6mm with 2% V_f and 3% V_f.



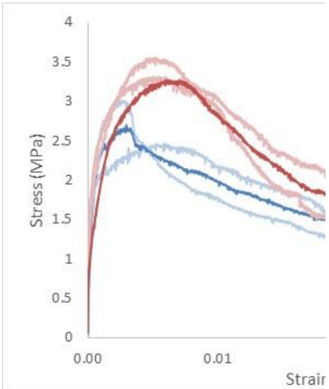


Fig 4b. Tensile stress-strain response of SFRGC -13mm with 2% V_f and 3% V_f.

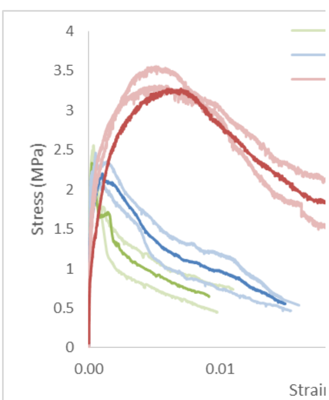


Fig 4c. Tensile stress-

strain response of
SFRGC 3% V_f 13mm,
6mm and 3hyb St (6+13).

As can be observed from the results of Fig. 4, the initial linear elastic phase is followed by a non-linear strain-hardening behavior up to the peak load only in case of specimens with 13mm long steel fibres or mixture of 6mm and 13mm long fibres. In case of specimens with 6mm length only, there was not any strain hardening after the linear part which is attributed to the poor bond between the geopolymer matrix and the steel fibres. The highest strength and post peak stress values were achieved in the specimens with 13mm length where the bond between the fibres and the matrix is improved. The peak load and post cracking behavior were improved in all the examined specimens as the fibres content was increased. All the examined specimens failed in a steel fibre pull out mode.

From the stress-strain curves of Fig. 4, the tensile strength at the peak load was calculated and the results are presented in Fig. 5.

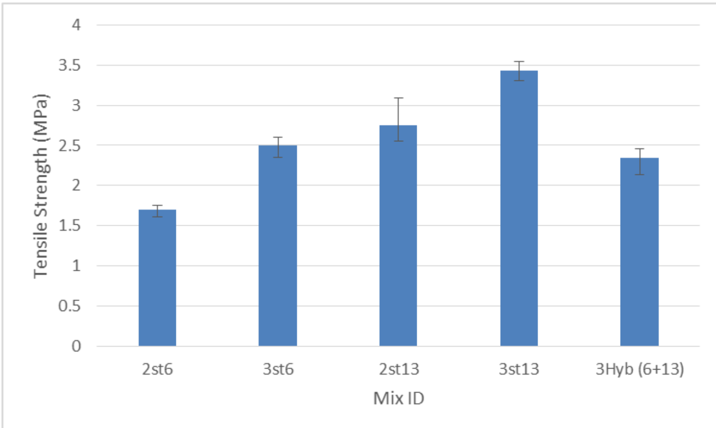
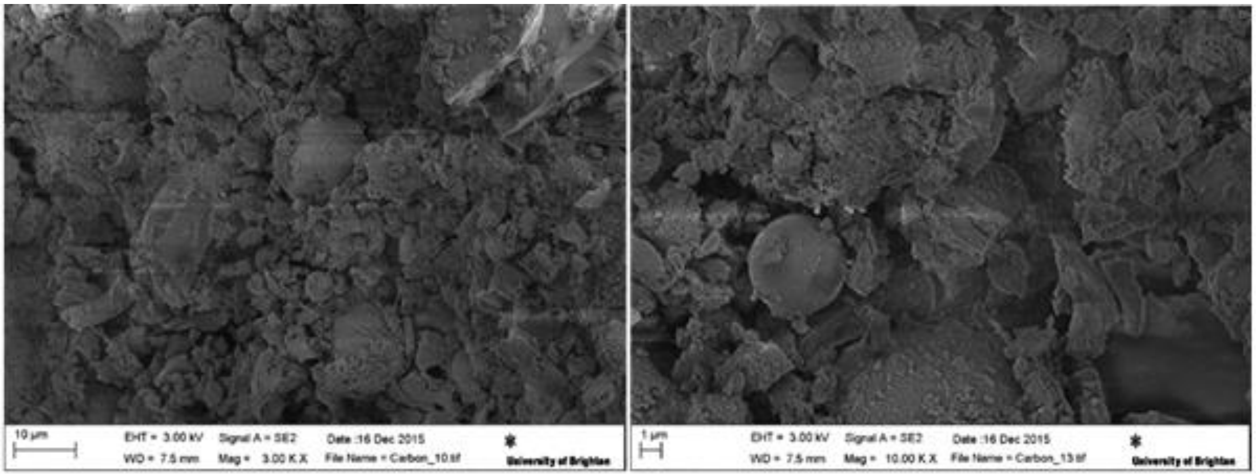


Fig. 5. Tensile strength of steel fibre reinforced geopolymer composite (SFRGC)

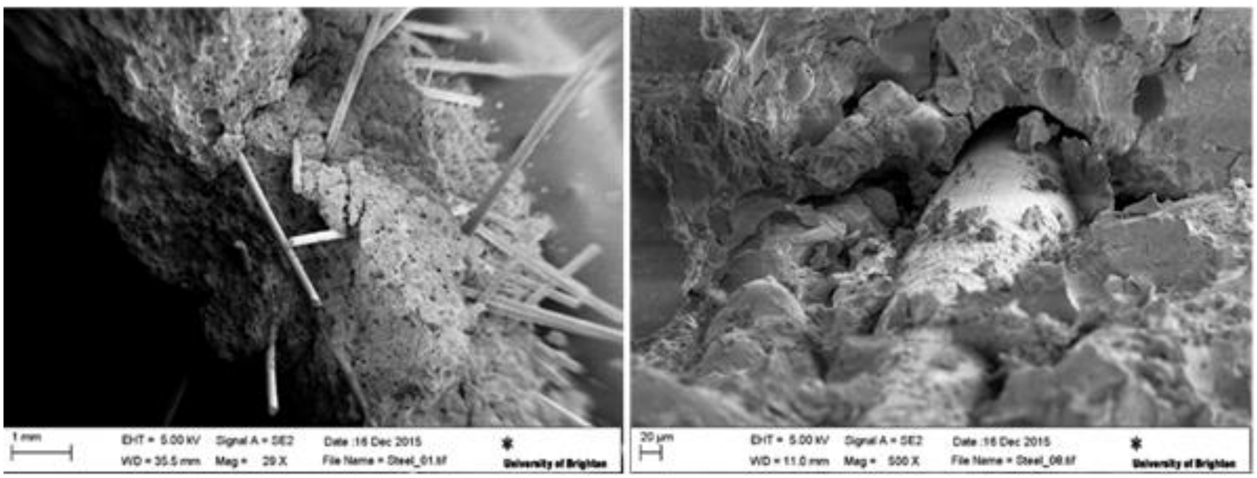
The experimental results indicate that the ultimate tensile strength is considerably increased as the steel fibre percentage and the length of the fibres are increased. Based on these results, the average tensile strength was increased 30% as fibre content was increased from 2% to 3% when 13mm steel fibre were used. The respective increment was found 15% when 6mm steel fibres were used.

3.3 Scanning electronic microscopy (SEM)

Scanning electron microscope (SEM) analyses were also conducted in the current study in order to provide in-depth understanding of the effect of the microstructure characteristics on the mechanical performance. SEM images of the plain and the steel fibre reinforced geopolymer composites after the end of the tensile tests are shown in fig (6 a-b).



(a)



(b)

Fig 6. Scanning electronic microscopy micrographs of geopolymer composite (a) Plain geopolymer mortar and (b) perpendicular to the fracture surface of steel fibre/geopolymer composites.

From the SEM images presented in Fig. 6b, a relative rough steel fibre surface with attached geopolymer hydration products can be observed. This observation is attributed to the relatively good bond between the geopolymer matrix and the fibres and the subsequent pull-out failure of the examined specimens. Also, the unchanged diameter of the steel fibres and the relatively clean exposed fibres' surface indicates negligible degradative effect of the alkaline geopolymer matrix on the steel fibres.

4. Conclusion

Novel cement-free geopolymer composites, reinforced with steel fibres and cured at ambient temperature, have been examined in this study. The geopolymer matrix was based on fly ash, slag and silica fume, and potassium silicate alkaline activator, and steel fibres were added in order to improve the mechanical properties of the examined material. The influence of fibres' length and dosage rates on the mechanical properties of SFRGCs has been investigated through compressive and direct tensile tests. The microstructure of the examined geopolymer mixtures was also assessed using SEM. The following conclusions can be drawn from the results presented in this paper:

- The compressive strength of the examined specimens was increased by 15-25 MPa when steel fibres were added to the mix. Highest compressive strength was achieved when 3% of steel fibres with 13mm length were used, and the compressive strength value in this case was found to be around 70 MPa.

- Regarding the behaviour in tension, strain hardening was observed only when 13mm fibres or combination of 13mm with 6mm steel fibres was used. In case of SFRGC with 6mm steel fibres, strain hardening was prevented due to the poor bond between the geopolymer matrix and the steel fibres.
- The relatively Good bond between the matrix and the steel fibres was also evidenced by the rough surface of the steel fibres which appeared in SEM images of specimens tested under direct tension, where pull-out failure mode was observed.

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