Interdependence between Structural Engineering and Construction Management
Edited by Ozevin, D., Ataei, H., Modares, M., Gurgun, A., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-6-2

MECHANICAL AND MICRO-STRUCTURE CHARACTERIZATION OF STEEL FIBER-REINFORCED GEOPOLYMER CONCRETE

SAID ELKHOLY and HILAL EL-HASSAN

Dept of Civil and Environmental Engineering, United Arab University, Al Ain, UAE

This paper aims to investigate the mechanical performance of steel fiber-reinforced geopolymer concrete made with fly ash and ground granulated blast furnace slag as blended aluminosilicate source material. To activate the binding phase, combinations of sodium silicate (SS) and sodium hydroxide (SH) solutions with three different molarities (8M, 10M, and 14M) were used. Steel fibers were added to the geopolymer concrete mix in varying proportions up to 3%, by volume. Constant binder, activator solution, and aggregate contents were adopted for all 13 mixes. Samples were cast and cured at ambient conditions for measuring the rheological and mechanical properties, including slump, modulus of elasticity, compressive strength, tensile splitting strength, and flexural strength. Experimental test results show that geopolymers made with higher molarity of SH were less workable but had improved mechanical performance. The effect of adding steel fibers on the mechanical performance was more apparent at an early age and in weaker geopolymer concretes. Additionally, scanning electron microscopy, differential scanning calorimetry, and Fourier transform infrared spectroscopy highlighted the co-existence of calcium aluminosilicate hydrate and sodium aluminosilicate hydrate gels.

Keywords: Rheological properties, Mechanical properties, Analytical models.

1 INTRODUCTION

To reduce the greenhouse gas emissions and consumption of natural resources, scientists and environmentalists recommend the replacement of cement by supplementary cementitious material (SCMs). Fly ash and ground granulated blast furnace slag (GGBS) are respective industrial by-products of the combustion of coal and production of steel. Fly ash and GGBS are highlighted as primary replacements to ordinary Portland cement (OPC) in concrete due to their pozzolanic properties and global abundance. Moreover, fly ash served as the main binder in an inorganic geopolymer concrete. Typically, it was activated through mixing with an alkaline solution of sodium silicate (Na_2SiO_3) and potassium or sodium hydroxide (KOH or NaOH). Research findings showed good compressive strength, low creep, acid resistance and low shrinkage (García-Lodeiro *et al.* 2007). It could also be used in severe environmental conditions with marine or heat exposure (Chanh *et al.* 2008, Kong and Sanjayan 2008, Zhang *et al.* 2010). Despite their superior performance, geopolymers have shown little resistance to cracking due to their brittle nature. For application in the construction industry, the tensile and flexural properties should be improved. Several studies, such as Al-Majidi *et al.* (2017), Aydın and Baradan (2013), Bernal *et al.* (2010) and Gao *et al.* (2017), investigated the mechanical properties of steel fiber-reinforced geopolymer composites.

This research investigates the mechanical performance of steel fiber-reinforced slag/fly ash blended geopolymer concrete. Fibers were added up to dosages of 3%, by volume. Three different molar concentrations of sodium hydroxide were used to assess the combined effect. Being locally abundant, desert dune sand served as a sustainable fine aggregate. The performance of geopolymer concrete mixes was evaluated in terms of compressive, tensile, and flexural strengths.

2 EXPERIMENTAL PROGRAM

2.1 Materials

Class F (ASTM C618 2015) fly ash and ground granulated blast furnace slag (GGBS) were used as the geopolymer binding material. Crushed stone was used as coarse aggregate with a nominal maximum size of 10 mm, specific gravity of 1660 kg/m^3, and water absorption of 1.5%. The aggregates were prepared to surface-saturated dry (SSD) condition. Desert dune sand served as fine aggregate. Its specific gravity and unit weights were 2.57 and 1670 kg/m^3, respectively. An alkali-activator solution was prepared as a mixture of sodium silicate (SS) and sodium hydroxide (SH). The mass chemical composition of the grade N SS solution was 26.3% SiO_2, 10.3% Na_2O, and 63.4% H_2O. The SH solution was formulated to a molarity of 14 (14M) by dissolving 97-98% pure NaOH flakes in tap water. Hooked-end steel fibers (specific gravity 7.9) with an aspect ratio of 65 and length of 35 mm were used. To ensure sufficient workability for mixes with high steel fiber content, a polycarboxylic ether polymer-based superplasticizer (SP) was used.

2.2 Geopolymer Concrete Mix Design

Thirteen slag/fly ash blended geopolymer concrete mixes with varying Sodium Hydroxide (SH) molar concentrations and fiber volume fractions were prepared. A 3:1 ratio of GGBS: fly ash was selected to eliminate the need for heat curing and to provide the concrete with sufficient workability for proper placing and finishing. The incorporation of steel fibers ranged from 0 to 3%. Three different molar concentrations of SH were used to assess the combined effect as shown in Table 1.

Table 1. Mix proportion of geopolymer concrete (kg/m^3).

Binder		**Aggregate**		**Activator**		**SP**	**Steel fiber volume (%)**
Fly Ash	GGBS	Dune Sand	Coarse	SS	SH (Molarity)		
125	375	550	1100	143	57(8M, 10M& 14M)	10	0.0~3%

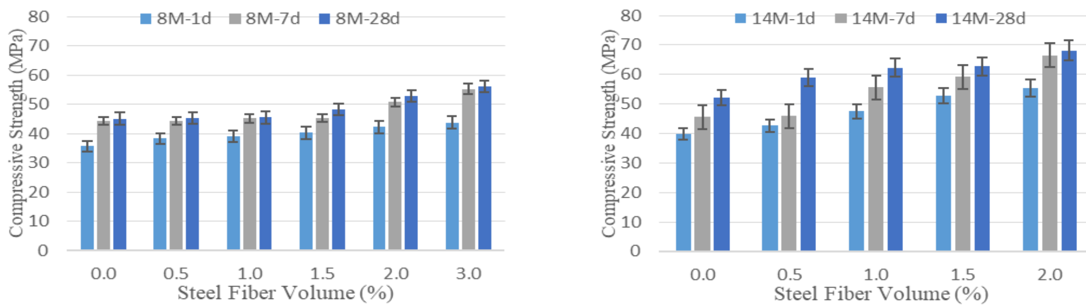
2.3 Sample Preparation

The alkali-activator solution was prepared two days prior to casting to allow for dissipation of heat associated with the exothermic chemical reactions of SH flakes with water and SH solution with SS solution. The dry components were mixed in a pan mixer for 3 minutes. The prepared solution was gradually incorporated into the dry components and mixed for 3 minutes to ensure homogeneity and uniformity. Superplasticizer was added a few seconds after the activator solution. For each mix, freshly-mixed geopolymer concrete was prepared as fifteen ϕ100 x 200 mm cylinders and three 100 x 100 x 500 mm prisms for subsequent mechanical testing. Specimens were cast into two layers, compact-vibrated for 10 seconds on a vibrating table, left to rest for 24 hours at ambient conditions, and then demolded. Subsequently produced geopolymers were kept at ambient conditions until testing age.

3 RESULTS AND DISCUSSION

3.1 Compressive Strength

The compressive strength development of geopolymer concrete mixes with respective 8M and 14 M SH is illustrated in Figure 1. On average, 81 and 97% of the 28-day compressive strength were obtained at 1 and 7 days of age, respectively for 8M geopolymers. Similarly, for 14M geopolymers, 78 and 89% of the respective 28-day compressive was reached within 1 and 7 days. The addition of steel fibers led to an increase in the load carrying capacity of geopolymers. An increase between 7 to 22% was observed after 1 day when 0.5 to 3% of steel fibers were added. At later ages of 7 and 28 days, up to 25% improvement in compressive strength was recorded with 3% steel fibers.



(a) 8M SH solution (b) 14M SH solution

Figure 1. Strength development of geopolymer made with different molarity of SH solution.

3.2 Indirect Tensile Strength

Figure 2 presents the splitting tensile strength as a function of steel fiber volume fraction incorporated for 8M, 10M, and 14M geopolymers at 28-day age. It can be seen that 14M geopolymer concrete was consistently superior to counterparts made with lower molarity of SH. This is well-aligned with compressive strength behavior. Geopolymers with 8M-SH increased by 7, 41, 55, 65, and 147% when 0.5, 1, 1.5, 2, and 3% of steel fibers were added, respectively. Clearly, the contribution of steel fibres to compressive strength was more significant at higher fiber dosages. On the other hand, 14M counterparts increased by 7, 22, 28, and 60% for similar steel fibers volume fractions.

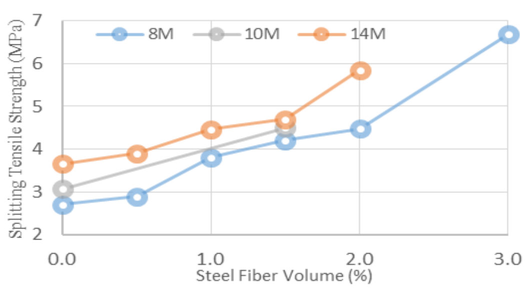


Figure 2. Splitting tensile strength fiber reinforced geopolymer concrete.

3.3 Flexural Strength

Figure 3 presents the flexural strength of plain and steel fiber-reinforced geopolymer concrete at 28-day age. An increase in flexural strength can be noted upon the incorporation of steel fibers. For 8M-geopolymers, a volumetric addition of fiber up to 1.5% could only enhance the flexural capacity by 5%. However, the effect of fiber addition was more pronounced at higher dosages of 2 and 3%. The associated increase in strength was 20 and 32%, respectively. Apparently, crack propagation through geopolymer concrete was retarded or arrested due to the incorporation of 2 to 3% steel fibers. An increase of 9% was also reported for 10M-geopolymers upon the addition of 1.5% steel fiber volume fraction. In contrast, a near-linear relation between the volume fraction of steel fibers and flexural strength increase was noted for 14M-geopolymers. On average, the flexural strength increased by 8% for every 0.5% volume fraction of steel fiber added. A comparison between geopolymers with constant steel fiber content and different molarity of SH (8M-1.5SF, 10M-1.5SF, and 14M-1.5SF) showed that higher molarity resulted in further increase in flexural strength.

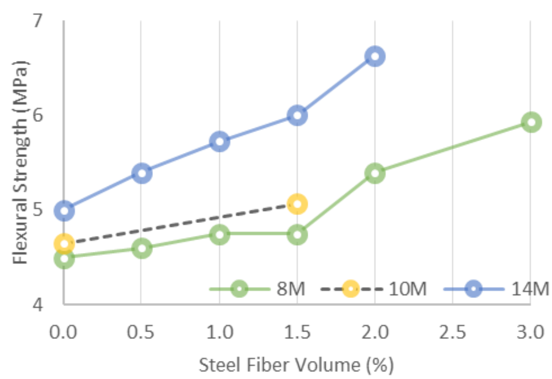


Figure 3. Flexural strength of 8M, 10M, and 14M geopolymer concrete.

3.4 Failure Modes

A comparison of the failure mode of plain and steel fiber-reinforced concrete cylindrical specimens after undergoing compression tests are shown in Figure 4. Plain geopolymer concrete made with slag and fly ash did not undergo an explosive failure at peak load as in fly ash-based geopolymers. Rather, it retained its original shape after the peak load. The crack propagation in the geopolymer binder was restricted under compression due to the transverse confinement effect of steel fibers and adequate bond with the geopolymeric matrix. Effectively, the addition of steel fibers led to higher compressive strength.

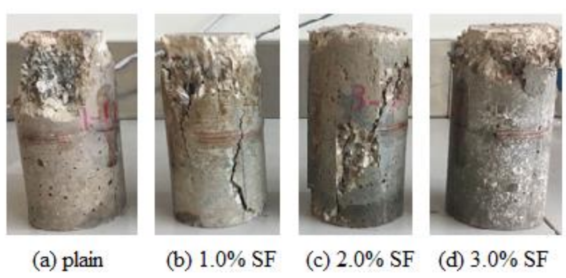


Figure 4. Compression failure modes of 14M-geopolymer concrete

Figure 5 shows the splitting tensile failure modes of plain and fiber reinforced geopolymers. It is clear from the figure that the extent of damage decreases as more fiber reinforcement is incorporated into the geopolymeric mixture. The failure transformed from a brittle to a more ductile behavior due to the inclusion of steel fibers. While the plain geopolymeric cylinder split into two parts, the cylindrical sample incorporating 3% steel fibers, by volume, remained completely intact.

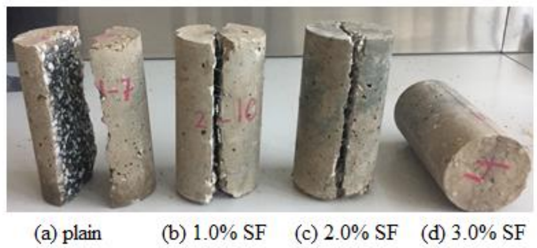


Figure 5. Splitting tensile failure modes of 14M-geopolymer concrete.

Figure 6 shows the flexural failure modes of plain and fiber-reinforced geopolymer concrete prisms. All cracks formed in the middle third and propagated nearly vertically upward. Plain geopolymer concrete of Figure 6(a) experienced fracture and separation of the prism into two parts. On the contrary, fiber-reinforced counterparts remained intact; higher load capacity was observed with higher volumetric fiber fractions.

(a) Plain

(b) 1.0% SF

(c) 2.0% SF

(d) 3.0% SF

Figure 6. Flexure failure modes of 14M-geopolymer concrete.

3.5 SEM and FTIR Analyses

The microstructure of plain geopolymer concrete was analyzed by 100 differential scanning calorimetry, 101 scanning electron microscopy), and Fourier transforms infrared spectroscopy. The micrographs of geopolymer concrete samples after 7 and 28 days did not significantly change. The FTIR spectra of concrete samples after 28 days showed larger quantities of reaction products and few water peaks.

3 CONCLUSIONS

The results of this study show that the mechanical performance of geopolymer concrete composed of Class F fly ash and slag depends on the molarity of SH. The mechanical properties of steel fiber-reinforced geopolymer composites were investigated. An increase in compressive, tensile and flexural strength was obtained using steel fibers in dosages up to 3%, by volume. The addition of steel fibers led to an increase in compression, tensile, and flexural strength. The effects of steel fibers in dosages on compression, splitting tensile and flexural failure modes were also reported.

Acknowledgments

The authors are grateful to the United Arab Emirates University for financial support through grants 31N305 and 31N282. The assistance of students and laboratory staff at the United Arab Emirates University is gratefully acknowledged.

References

Al-Majidi, M. H., Lampropoulos, A., and Cundy, A. B., Steel Fibre Reinforced Geopolymer Concrete (SFRGC) with Improved Microstructure and Enhanced Fibre-Matrix Interfacial Properties, *Construction and Building Materials*, 139, 286-307, 2017.

ASTM C618, *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, ASTM International, West Conshohocken, PA, 2015.

Aydın, S., and Baradan, B., The Effect of Fiber Properties on High Performance Alkali-Activated Slag/Silica Fume Mortars, *Composites Part B: Engineering*, 45(1), 63-69, 2013.

Bernal, S., De Gutierrez, R., Delvasto, S., and Rodriguez, E., Performance of an Alkali-Activated Slag Concrete Reinforced with Steel Fibers, *Construction and Building Materials*, 24(2), 208-214, 2010.

Chanh N V, Trung B D, and N, V. T., *Recent Research on Geopolymer Concrete*, Proc., the 3rd ACF International Conference-ACF/VCA, 2008.

Gao, X., Yu, Q. L., Yu, R., and Brouwers, H. J. H., Evaluation of Hybrid Steel Fiber Reinforcement in High Performance Geopolymer Composites, *Materials and Structures*, 50(2), 165, 2017.

García-Lodeiro, I., Palomo, A., and Fernández-Jiménez, A., Alkali–Aggregate Reaction in Activated Fly Ash Systems, *Cement and Concrete Research*, 37(2), 175-183, 2007.

Kong, D. L. Y., and Sanjayan, J. G., Damage Behavior of Geopolymer Composites Exposed to Elevated Temperatures, *Cement and Concrete Composites*, 30(10), 986-991, 2008.

Zhang, Z., Yao, X., and Zhu, H., Potential Application of Geopolymers as Protection Coatings for Marine Concrete: II. Microstructure And Anticorrosion Mechanism, *Applied Clay Science*, 49(1–2), 7-12, 2010.