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Early-Age Properties of Slag-Fly Ash Blended Geopolymer Concrete Reinforced with Glass Fibers – A Preliminary Study

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Abstract – This research investigates the effect of additional water content, glass fibers addition, glass fiber length, and the handling time on the workability, 1- and 7-day compressive strength, and 7-day splitting tensile strength of slag-fly ash blended geopolymer concrete. The additional water content ranged from 0 to 100 kg/m^3. Two types of glass fibers were used with lengths of 24 and 43 mm and incorporated by up to 2 and 1.5%, by volume, respectively. Also, the handling time, representing the time from mixing to casting, was varied. The experimental results showed that the additional water content led to a significant increase in the slump and decrease in the 1- and 7-day compressive strengths of plain geopolymer concrete. A value of 75 kg/m^3 was required to attain a slump of 150 mm and 7-day compressive strength of 35 MPa. Furthermore, the addition of 24-mm long glass fibers reduced the slump and increased the compressive and splitting tensile strength by up to 23 and 40%, respectively, compared to the plain control mix. Longer glass fibers (43 mm) resulted in further slump loss and increase in the splitting tensile strength, while the compressive strength was unaffected. Extending the handling time led to lower workability and limited impact on the mechanical properties.

***Keywords*:** Glass fiber, geopolymer concrete, fly ash, slag, slump, compressive strength, splitting tensile strength.

1. Introduction

The demand of concrete by the construction industry has significantly increased over the past few decades, owing to economic development and population growth. The average production of concrete is 15 billion tons per year with more than one cubic meter being produced per capita [1]. One of its main components, cement, has been associated with high consumption of energy, depletion of non-renewable natural resources, and release of substantial greenhouse gases. With 4.8 billion tons being produced globally per year, the cement industry has led to an increase in the concentration of carbon dioxide and is accountable for 5-7% of the global carbon dioxide emissions [2, 3]. As a result, it is critical to find a more sustainable alternative binding material to reduce the environmental footprint of the construction industry.

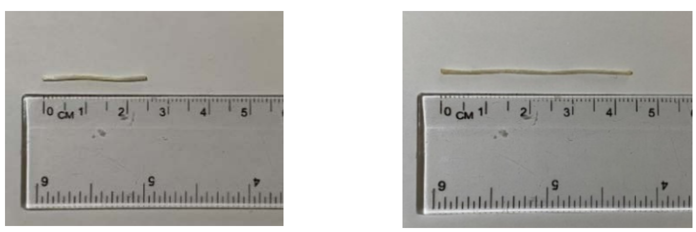
Supplementary cementitious materials (SCMs) have been used as a partial replacement to cement in conventional concrete. However, the full replacement (100%) of cement with SCMs was not possible in conventional concrete that underdoes a hydration reaction. In turn, several studies proposed the use of SCMs as the sole binder in a cement-free inorganic geopolymer concrete. Such SCMs, which are typically industrial by-products, were chemically activated using alkaline solutions, including sodium silicate and sodium hydroxide. Recent lifecycle assessment study resulted in a minimum of 25% reduction in the greenhouse emissions, energy consumption, and water utilization for such innovative concrete products as a more sustainable alternative to the conventional cement-based concrete [4]. Moreover, such concrete product can be beneficial in recycling industrial wastes rather than disposing them in landfills or stockpiles.

The use of these industrial wastes in geopolymer concrete has been extensively investigated in the past [5-14]. Yet, several past literature aimed to enhance the structural performance of such concrete through the inclusion of steel fibers. In his review, Rashad [15] concluded that steel fibers had an adverse effect on the workability and porosity of the geopolymer concrete, but positively impacted the mechanical strength, density, ductility, and shrinkage. In other work, the effect of steel fibers on fly ash/slag blended geopolymer concrete was studied [16-21]. Results revealed that increasing steel fiber volume fraction reduced the workability and enhanced 28-day mechanical strength. In similar studies, Gao et al. [22], Devika and Nath [23], and Prabu et al. [24] investigated the influence of steel fibers up to 1% volume fraction on fly ash- and slag-based geopolymer concrete. Workability and drying shrinkage was found to have reduced, while compressive strength and porosity increased. Furthermore, Saloni et al. [25] conducted a study on high-silica rice husk ash-based geopolymer paste incorporating basalt fibers. Results showed that the initial and final setting times and mechanical properties increased with the increase in basalt fibers. In other work, Lakshmi and Rao [26] and Nematollahi et al. [27] evaluated the performance of fly ash-based geopolymer concrete incorporating glass fibers by up to 4% volume fractions. Results showed that increasing the amount of glass fibers caused a decrease in the workability and increased the tensile, compressive, and flexural strengths. Conversely, Sathanandam et al. [28] reported limited change in workability and a reduction in the compressive strength when more than 0.3% glass fibers, by volume, were added to fly ash-based geopolymer.

Summarizing the literature, glass fibers have potential to enhance the performance of geopolymer. However, no studies have been carried out to evaluate the fresh and hardened properties of slag-fly ash blended geopolymer concrete incorporating glass fibers. This research aims to examine the early-age strength and workability properties of glass fiber-reinforced slag-fly ash blended geopolymer concrete. The effect of additional water content, different lengths and volume fractions of glass fibers, and handling time on the performance of geopolymer concrete was assessed.

2. Materials

The geopolymer binder comprised a blend of slag and fly ash as the aluminosilicate precursor binding material. The binder was activated in an alkaline solution made of grade N sodium silicate (SS) and 14 M sodium hydroxide (SH) solutions. Fine aggregates were locally sourced in the form of desert dune sand. The chemical composition, particle size distribution, scanning electron microscopy, and X-ray diffraction patterns of the slag, fly ash, and dune sand can be found elsewhere [18]. Their respective unit weights are 1209, 1262, and 1663 kg/m^3. Furthermore, natural dolomitic limestone with a nominal maximum size of 19 mm served as the coarse aggregates in geopolymer concrete mixes. It had a dry rodded density of 1635 kg/m^3, absorption of 0.2%, abrasion mass loss of 16%, surface area of 2.5 cm^2/g, and specific gravity of 2.82. These aggregates were used in saturated surface dry condition to prevent the absorption of mixing water. Also, tap water and a polycarboxylic ether polymer-based superplasticizer were employed to enhance the workability. Glass fibers having two different lengths of 24 and 43 mm were used, as shown in Figure 1. Since the lengths are different, the aspect ratio of the shorter fiber is 35 while the longer is 62. Their diameter, tensile strength, Young’s modulus, and specific gravity are the same with respective values of > 1000 MPa, 42 GPa, and 2.0.



(a) (b)

Figure 1. Glass fiber with length (a) 24 mm and (b) 43 mm

3. Mixture Proportioning

Geopolymer concrete mixtures were designed to achieve a 28-day cube compressive strength of 35 MPa and slump of 150 mm. Table 1 summarizes the mixes evaluated in this study. Slag and fly ash were blended in a 3:1 ratio due to the superior performance of this specific blend compared to others [18, 29]. The SS-to-SH ratio and SH molarity were fixed to 1.5 and 14 for all mixes, respectively, as higher values did not seem to have a major impact on the performance of slag-fly ash blended geopolymers [11]. The superplasticizer content was kept at 2.5%, by binder mass, for all mixes. The test parameters included the additional water, glass fiber volume fraction, and handling time of the mix. The additional water was incorporated into the mix to increase the workability and ranged from 0 to 100 kg/m^3. Once a strength of 35 MPa and slump of 150 mm were obtained, the water content was deemed optimum and fixed for the remaining mixes. The glass fiber volume fraction was varied among 0, 1, 1.5, and 2%. It is worth noting that the original experimental program did not include 1.5% volume fraction (only 0, 1, and 2%). However, a trial mix incorporating 2% of the 43-mm long, by volume, showed that it could not be cast. As such, it was limited to 1.5%. This volume fraction was also adopted for the 24-mm long fibers for proper comparison. The final parameter, the handling time, was evaluated for geopolymer concrete mixes incorporating 0 and 1% glass fibers, by volume. It represented the time taken from the start of mixing to the end of casting. The time varied from limited (4-5 minutes) to extended (9-10 minutes). Based on these proportions, the mixes were labelled as GCw-GFv/l-t, where w represents the amount of water content added to the mix in kg/m^3, v is the volume fraction of glass fiber (%), l represents the length of glass fiber (in mm), and t expresses the handling time. For instance, GC50-GF0.5/24-L represents a geopolymer concrete mixture with 50 kg/m^3 of water content, 0.5% volume fraction of 24 mm-long glass fibers, and handled over a limited time of 4-5 minutes.

Table 1: Mixture proportions of geopolymer concrete (in kg/m3)

Mix ID	Aluminosilicate materials		Fine aggregates	Natural Coarse aggregates		Alkaline activator		SP	Water Content	Glass fiber (%)	Casting time	Study Parameter
	Slag	Fly ash	Dune Sand	10 mm	20 mm	SS	SH					
GC0-GF0-L	225	75	725	363	847	99	66	7.5	0	0	Limited	Effect of additional water content
GC10-GF0-L	225	75	725	363	847	99	66	7.5	10	0	Limited	
GC50-GF0-L	225	75	725	363	847	99	66	7.5	50	0	Limited	
GC75-GF0-L	225	75	725	363	847	99	66	7.5	75	0	Limited	
GC100-GF0-L	225	75	725	363	847	99	66	7.5	100	0	Limited	
GC75-GF1.0/24-L	225	75	725	363	847	99	66	7.5	75	1	Limited	Effect of glass fiber content
GC75-GF1.5/24-L	225	75	725	363	847	99	66	7.5	75	1.5	Limited	
GC75-GF2.0/24-L	225	75	725	363	847	99	66	7.5	75	2	Limited	
GC75-GF1.0/43-L	225	75	725	363	847	99	66	7.5	75	1	Limited	Effect of glass fiber length
GC75-GF1.5/43-L	225	75	725	363	847	99	66	7.5	75	1.5	Limited	
GC75-GF0-E	225	75	725	363	847	99	66	7.5	75	0	Extended	Effect of handling time
GC75-GF1.0/24-E	225	75	725	363	847	99	66	7.5	75	1	Extended	

4. Sample Preparation

The geopolymer concrete samples were prepared and cast under ambient laboratory conditions with temperature of 23±2°C and relative humidity of 50±5%. To formulate the alkaline activator solution, sodium hydroxide flakes were first mixed with a specific amount of water to create the 14 M SH solution. After the heat generated from the exothermic reaction was dissipated and the solution reached room temperature, the sodium silicate solution was added. The newly-formed mixture was also allowed to dissipate the heat from the second exothermic reaction of SS and SH. This alkaline activator solution was then mixed with the additional water, as applicable, and gradually added to the pre-mixed dry ingredients, slag, fly ash, coarse aggregates, and dune sand. Freshly-prepared geopolymer concrete was then cast into 100 mm cubes and 100 mm x 200 mm cylinders (diameter x height) and vibrated for 10 seconds on a vibration table. The entire casting process was carried out within 4-5 minutes but was extended in two mixes (GC75-GF0-E and GC75-GF1.0/24-E) for 9-10 minutes by leaving the sample in the mixer for 5 minutes. Samples were then covered with plastic wrap to limit solution evaporation, demoulded after 24 hours, and then placed in open air until testing age.

5. Performance Evaluation

The fresh properties of the slag-fly ash blended geopolymer concrete were evaluated using the slump, as per ASTM C143 [30]. The early-age hardened properties were characterized by the compressive and splitting tensile strength. The compressive strength was determined in accordance with ASTM C39 [31] at the ages of 1 and 7 days. Conversely, the splitting tensile strength was measured at 7 days following the procedure of ASTM C496 [32]. For each mechanical strength test, three replicate specimens were used to obtain an average.

6. Results

6.1 Slump

Figure 2 shows the slump of slag-fly ash blended geopolymer concrete mixes. A comparison among the first five mixes demonstrates the impact of additional water on the slump. Results show that adding 10, 50, 75, and 100 kg/m^3 of water increased the slump by 0, 50, 165, and 230 mm. This improvement in workability is apparently due to the increase of free water, which has no role in the chemical reaction [8]. Apparently, the required slump of 150 mm could be attained by 75 kg/m^3 of water. As such, the remaining mixtures incorporated this water content.

The effect of glass fiber addition on the slump of geopolymer concrete was evaluated. The inclusion of 1, 1.5, and 2% short glass fibers (24 mm), by volume, decreased the slump to 75, 60, and 0 mm, representing 55, 64, and 100% reductions, respectively, compared to the plain concrete mix (GC75-GF0-L). In turn, the addition of 1 and 1.5% volume fraction of long glass fibers (43 mm) led slump values of 50 and 15 mm, corresponding to respective decreases of 70 and 91%. This shows that longer fibers had a more detrimental impact on the workability of slag-fly ash blended geopolymer concrete. It is believed that more geopolymeric paste would be needed to encapsulate the longer fibers, leaving less paste for workability purposes.

Extending the handling time of the geopolymer concrete was also examined for plain and glass fiber-reinforced mixes. In comparison to the mix GC75-GF0-L, increasing the handling time by 5 minutes reduced the slump by 45%, from 165 to 90 mm. Adding 1% glass fiber volume fraction further lowered the slump to 60 mm. This value was inferior to that of the mix with shorter handling time (GC75-GF1.0/24-L) having a slump of 75 mm. This shows that longer handling times can lead to reduced slump with more pronounced loss in workability in mixes without glass fibers.

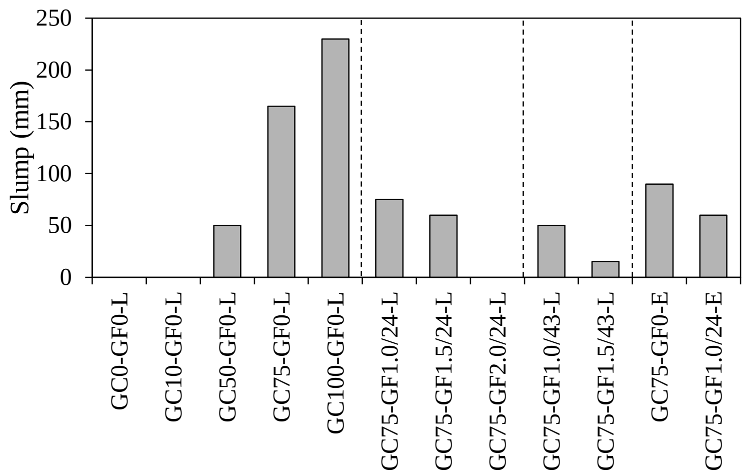


Figure 2. Slump values of geopolymer concrete mixes

6.2 Compressive Strength

Figure 3 presents the compressive strength of slag-fly ash blended geopolymer concrete. At the age of 1 day, the control mix with limited mixing time and no glass fibers had a compressive strength of 36.9 MPa. The addition of 10, 50, 75, and 100 kg/m^3 of water resulted in strength values of 36.3, 25.4, 22.2, and 16.5 MPa. This highlights the adverse impact of additional water on the compressive strength. At 7 days, a similar trend was noted, i.e. 7-day strength decreased with water content, except that the addition of 10 kg/m^3 of water led to a slight increase in compressive strength. Nevertheless, the 35-MPa design strength was attained when 75 kg/m^3 of water were added to the geopolymer mix. This mix served as the reference for the remaining analysis. Also, it is worth noting that the dispersion of test results, evidenced by the error bars of Figure 3, is relatively low with high precision and repeatability and limited uncertainty.

The effect of adding short (24 mm) glass fibers on the 1-day compressive strength was examined. The inclusion of 1, 1.5, and 2% glass fiber volume fractions increased the compressive strength by 6, 14, and 23%, respectively, compared to the plain control mix (GC75-GF0-L). Similar findings were noted at the age of 7 days, with respective increases of 4, 9, and 14%. This shows that the addition of glass fibers improved the compressive strength, owing to its bridging effect, but it was slightly more effective at 1 day, when the matrix was in its early hardening stages.

The compressive strength was also affected by the incorporation of long (43 mm) glass fibers. While the addition of 1 and 1.5% volume fractions decreased the 1-day compressive strength by 21 and 9%, respectively, they had an insignificant influence on the strength at 7 days. Nevertheless, the strength gain in these glass fiber-reinforced mixes was more apparent than any other counterparts. It is clear that short glass fibers were slightly more effective in improving the compressive strength than long counterparts.

Figure 3 also presents the compressive strength of mixes with extended handling time. For plain geopolymer mixes, the additional time resulted in 22 and 10% higher 1- and 7-day compressive strength, respectively. Conversely, increases of 10 and 3% were noted for geopolymer mixes reinforced with 1% glass fiber, by volume. Such results confirm that longer handling time did not negatively impact the compressive strength. Similar findings were noted in previous work on plain fly ash-based geopolymer concrete [33].

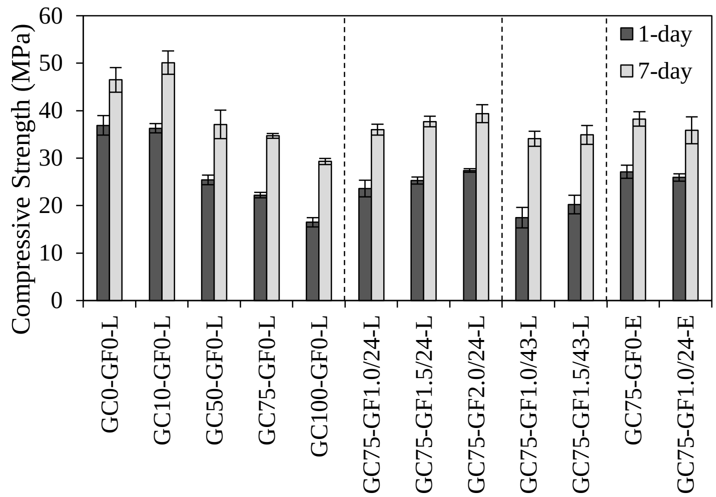


Figure 3. Compressive strength of geopolymer concrete mixes

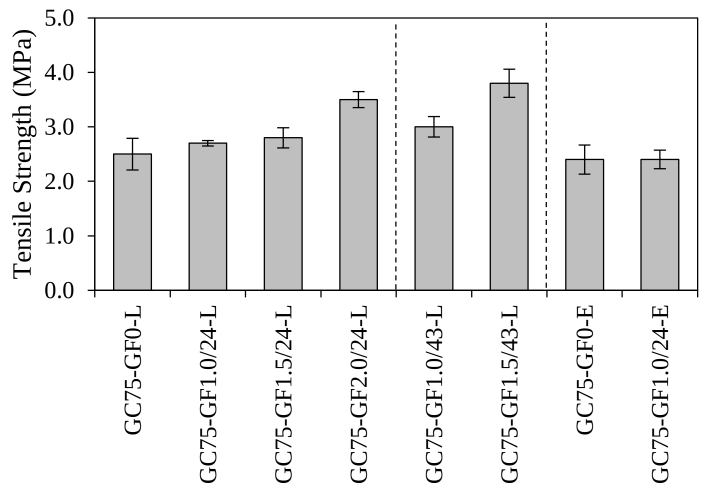


Figure 4. Splitting tensile strength of geopolymer concrete mixes

6.3 Splitting Tensile Strength

The splitting tensile strength (f_{sp}) of 7-day slag-fly ash blended geopolymer concrete is illustrated in Figure 4. For the control mix, GC75-GF0-L, the value of f_{sp} was 2.5 MPa. The addition of 1, 1.5, and 2% of the short glass fibers increased f_{sp} by 8, 12, and 40%, respectively, compared to the control mix. Furthermore, the inclusion of the long glass fibers on f_{sp} was evaluated. The incorporation of 1 and 1.5% glass fiber volume fraction resulted in 20 and 52% higher f_{sp}. Clearly, longer glass fibers led to superior f_{sp}, owing to the capacity of glass fibers to bridge the cracks and delay their formation and propagation. Also, it is worth noting that geopolymer concrete reinforced with 1.5% volume fraction of 43-mm long fiber had higher f_{sp} than counterparts made with 2% volume fraction of 24-mm long glass fibers. Moreover, extending handling time of geopolymer concrete had no effect on f_{sp}. Also, it should be noted that the dispersion of test results, evidenced by the error bars of Figure 4, is relatively low with high precision and repeatability and limited uncertainty.

7. Conclusions

This paper examines the effect of additional water content, inclusion of glass fibers, changing the glass fiber length, and extending handling time on the workability and early-age strength of slag-fly ash blended geopolymer concrete mixes. The experimental program entailed determining the slump, compressive strength, and splitting tensile strength. The following are the concluding remarks:

i) The slump increased from 0 to 230 mm upon adding up to 100 kg/m^3 of water to the geopolymer mix. The optimum additional water content to attain a slump of 150 mm was 75 kg/m^3. Such additional water reduced the compressive strength by 40%.

ii) The inclusion of short (24 mm) glass fibers reduced the slump by 55, 64, and 100% with the addition of 1, 1.5, and 2% volume fractions, respectively. An opposite trend was noted for compressive and splitting tensile strength, whereby the respective strengths increased by up to 23 and 40%.

iii) The use of long (43 mm) glass fibers had a more detrimental impact on the slump than short glass fibers with reduction of up to 91% upon adding 1.5% glass fiber, by volume. The compressive strength was not impacted by the inclusion of long glass fibers and results were comparable to the plain control mix. Conversely, the splitting tensile strength was up to 50% higher than that of the control with results confirming that longer glass fibers led to superior splitting tensile strength. This is primarily owed to the bridging capacity of glass fibers and their ability to limit crack formation and propagation.

iv) Longer handling times led to 45% lower slump with more a pronounced loss in workability in the mix without glass fibers. In contrast, it had a slightly positive impact on the compressive strength and did not affect the splitting tensile strength.

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