" Influence of Steel Fibers on the Fracture Behavior of Geopolymer Mortar Composite"

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ABSTRACT

Geopolymers/alkali-activated binders and their composites have gained more and more attention around the globe because of their high early strength, outstanding durability, and minimal carbon emission during manufacture. This study examined how steel fibers affected geopolymer mortar's microstructure and fracture behavior. The experimental procedure includes adding 1, 2, and 3 v_f% of steel fibres to a mixture consisting of 20% silica fume modified GGBS-based geopolymer mortar. The results revealed that the addition of steel fibers led to a clear improvement in the fracture behavior of geopolymer mortar by retarding and preventing the growth of cracks generated by stresses. The results also showed significant improvement in the splitting tensile strength and bending strength of geopolymer mortar, particularly with the addition of low and medium steel fibers.

Keywords: Geopolymer, Mortar, Steel fibers, Fracture, Composite.

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INTRODUCTION

Compared to Portland cement binders, alkali-activated materials, commonly known as geopolymers, exhibit substantial mechanical properties and structural integrity(Guo et al. 2018, Bhutta et al. 2019, Li et al. 2022). Given that they permit a wide variety of implementations, like fire-resistant materials (Wongsa et al. 2020, Das et al. 2021, Sahin et al. 2021), thermal insulation (Guo et al. 2021, Meng et al. 2022, Zhang et al. 2022), and thermal energy storage concrete, geopolymers have attracted the greatest interest nowadays. Due to these features, several researchers investigated various methods for enhancing these materials' qualities. Ren and Li (Ren et al. 2022) investigated how the reinforcing index (RI) of polyethylene (PE) fibers affected several geopolymer mortar toughness characteristics. The PE fiber reinforced geopolymer composite has superior RI values than the portland cement-based composite due to the increased bonding strength between the matrix and fibers in geopolymer. The number of cracks grew from 1 to more than 20, and the fracture shape varied from straight to very zigzagging as RI increased from 0 to 691.2.

Şahin. et al. investigated the impact of three different basalt fiber proportions on metakaolin-based geopolymers prepared with three distinct aggregates (Şahin et al. 2021). The findings showed that basalt fibers were beneficial, particularly in concentrations between 0.8 and 1.2%. When the findings were analyzed, t increased flexural strength by up to 50% and compressive strength by up to 25%.. Additionally, the outcomes were appropriate for the application despite the fact that geopolymers manufactured using recycled aggregate had lower qualities to the others. By creating a harder and more dense structure than others, the basalt sand impact produced better outcomes.

Fernandes and Penteado (Gomes et al. 2020) analyzed the fracture parameters of geopolymer concrete reinforced by steel fibers using varying percentages of 0.25% and 0.50vf% of concrete.

The results confirmed the important role of fibers in reducing the spread of cracks and preventing brittle fractures in the composite. All the properties of the concrete were also improved by adding the steel fibers, and the optimum value was 0.50% of the concrete compared to the fiber-free models.

1. MATERIALS

2.1. GGBS (Ground Granulated Blast Furnace Slag)

GGBS was brought from the Iraq Sika Company for Building Materials. It was examined in the Central Laboratories Dept, Geological Survey. Table 1 shows the chemical analysis of the slag, while Table 2 presents the slag's physical characteristics, which met the specifications according to (ASTM C 989) .

2.2. Silica Fume (SF)

Due to its high silica concentration and ultra-fine particle fineness, silica fumes (SF) is an excellent pozzolanic materials. Silica fume was brought from Iraq Sika Company for Building Materials. Table 3 displays the specifications of the silica fume.

Table 1. Chemical Analysis of GGBS.

Oxide	Content (%)
SiO_2	29.01
Al_2O_3	14.99
Fe_2O_3	0.53
SO_3	1.13
MgO	8.60
CaO	39.23
LSF	0.39

Table 2. GGBS physical features.

Properties	Values
Physical Form	Powders
Surface Area, m^2/kg	5338
Specific Gravity	3.2
Color	Light Grey

Table 3. Specifications of Silica Fume.

Parameters	Standard Value
Loss on Ignition (LOI)	3%max
Bulk Density	350-700 Kgkg/m^3
Percent Retained on 45 µm (325 sieves)	2.0% max
Moisture Content (H_2O)	1.0% max
Silicon Dioxide (SiO_2)	96% min

2.3. Fine Aggregates

In this study, natural fine aggregates with a highest size of 4.75 mm were employed from the Al-Ekhadir area in Karbala Governorate. Before using it, it was cleaned. Tables 4 and 5 display fine aggregates' chemical, grade, and physical properties that meet Iraqi standard requirements. IQS (No. 45/1984).

2.4. Admixture

A high-range water reducer type (MasterGlenium®54 superplasticizer (SP)) provided by Master Builders Solutions Dubai, UAE facility was utilized in this work In order to enhance the workability of the geopolymer mortar.

2.5. Additional Water

According to the Iraqi standards IQS No. 1703, distilled water was used to dissolve the caustic soda flakes, and tab water was used as extra water in the geopolymer mix design to improve the workability of the paste of geopolymer mortar.

2.6. Alkaline Solution

The sodium hydroxides and sodium silicates solutions were combined to create the alkaline solution, with a constant Na2SiO3/NaOH ratio of 2.5:1. The sodium hydroxide solution utilized had a 15 molarity content.

2.7. Steel Fibers

Cold drawn hooked ends steel fibers with 0.2 mm diameter and 12 to 14 mm length were used as a reinforcing phase within the geopolymer mortar paste.

2. MIX DESIGN

The mixes design of prepared geopolymer mortar composites are represented in Table 6.

Table 4. Natural fine aggregate gradings.

Sieve No.	Sieve size(mm)	Passing weight (%)	Spec. Limit according to IQS No45 / 1984 zone (2)
1	9.5	100	100
2	4.75	90.55	90-100
3	2.36	78.31	75-100
4	1.18	63.1	55-90
5	0.6	43.51	35-59
6	0.3	14.64	8-30
7	0.15	0.02	0-10

Table 5. Natural fine aggregate's characteristics.

Characterestics	Test Result	Iraqi Standard IQS 45-1984Limitations
Density (Kg/m^3)	1598	----
Specific gravity	2.7	----
Absorption (%)	0.71	----
Fineness modulus	3.1	----
Materials that pass through 75 µm sieve	1.3	3% maximum
Sulfate content (%)	0.36	0.5 percent maximum

Table 6. Mix Design of geopolymer mortar composites.

Mix	Slag (g)	Fine aggregate (g)	Na_2SiO_3:NaOH 2.5:1	NaOH (15 M)	Silica fume(wt.%)	Silica Fume (g)	Steel fibers (V_f%)
G0	240	600	117.9	47.1	20%	60	-
G1	240	600	117.9	47.1	20%	60	1%
G2	240	600	117.9	47.1	20%	60	2%
G3	240	600	117.9	47.1	20%	60	3%

3. EXPERIMENTAL PROCEDURE

A total of 4 geopolymer mortar composites were prepared with varying volume fractions of 1, 2, and 3vf% steel fibers addition. The dry ingredients (slag, fine aggregate, silica fume, steel fibers) have been mixed manually for approximately 5 to 10 mins. The alkaline solution was added to the dry materials, followed by a plasticizer and water. The mixing was continued for a further 4 min to produce the fresh mortar. To certify the homogeneity of the mixture, the total time of the mixing was approximately 10 to 15 minutes. After the termination of the mixing procedure, the geopolymer mortar was poured into a steel mold according to the geometry and dimensions required. Before pouring the mixture, the steel molds were covered via an extremely thin oil layer to prevent any potential adhesions between the mixture and the internal surfaces of the molds. The pouring process was done in three layers, and each layer was shocked for 1 to 2 min through the vibrating table based on mold type to remove the voids and achieve proper compaction. After the casting, the mold surface was smoothed and left for 24 hours at ambient temperature before the curing process. The curing process was done at ambient temperature for 7 and 28 days.

4. RESULTS AND DISCUSSION

5.1. Scanning Electron Microscope (SEM) Characterization

In order to investigate the microstructure of prepared geopolymer mortar and the influence of steel fibers on the microstructure of geopolymer mortar, SEM characterization was employed. Figure 1 shows the SEM image of silica fume modified geopolymer mortar at 28-day curing. According to the attained image, it was observed that the microstructure of 20% silica fume modified geopolymer mortar has a fine, homogenous, and dense microstructure due to the enhancement in the polymerization process and forming the gel phase, which fills the pores within the structure.

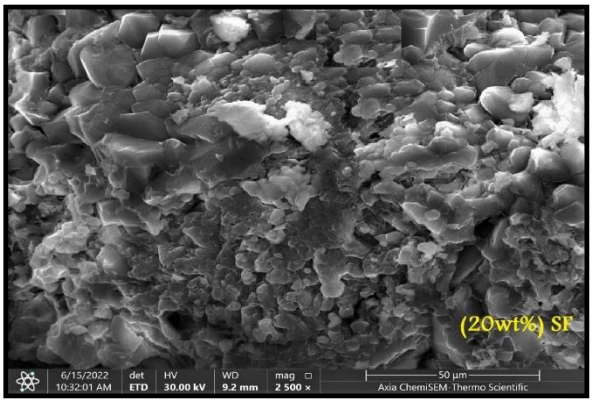
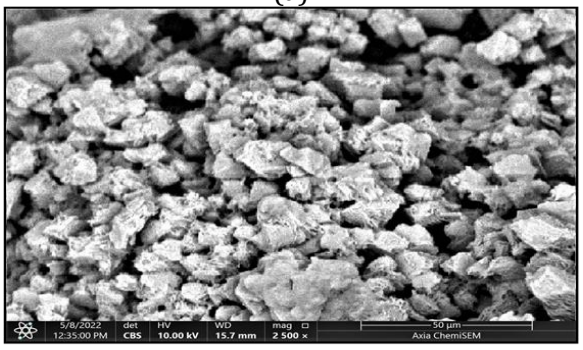


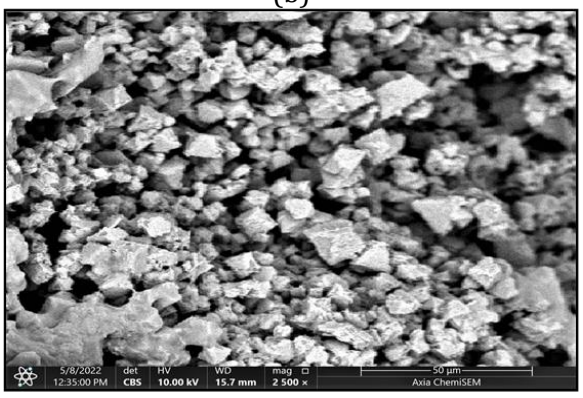
Figure 1. SEM Image of (20%) Silica Fume Modified Geopolymer Mortar Cured at 28 Day.

For the addition of the steel fibers, Figure 2 (a,b,c) displays the microstructure of 20% silica fume modified geopolymer mortar reinforced with different volume fractions of 1, 2, and 3% steel fibers, respectively. It was seen that there is a good dispersion of these fibers within geopolymer mortar structure, especially at a low volume fraction of 1% compared with the higher volume fraction of 3%. Some accumulations of steel fibres were observed, resulting in porosity within the structure.

(a)



(b)



(c)

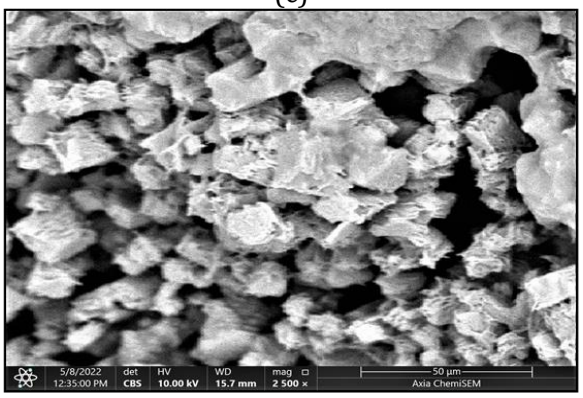


Figure 2. SEM Image of Geopolymer Mortar with 20wt% Silica Fume and (a)1%, (b) 2%, and (c) 3v_f% Steel Fibers.

5.2. Compressive Strength

Figure 3 presents the changes in the compressive strength values of 20% silica fume modified geopolymer mortar reinforced with 1, 2, and 3% volume fractions of steel fibers at different curing times. The experimental results exhibited that the difference in compressive strength is significantly influenced by curing time and fibers addition. The tests were carried out at different curing times of 7 and 28-day, respectively, in 3 sample sets. A higher exothermic reaction between CaO and silica fume powder in GGBS was discovered to enhance compressive strength estimates with curing time. This reaction will improve geopolymerization by producing more N-(C)-A-S-H and C-S-H gelling. These gels increase the hardened properties of the mixture and improve the bonding between the constituents of geopolymer mortar, causing more compressive strength values. In addition, the high molarity of the alkaline solution will activate the precursors to generate more dissolved ion species, enhancing the geopolymerization process of geopolymer pastes.

On the other hand, the obtained results showed a clear improvement in the compressive strength when adding a 1vf% of steel fibers to the mortar due to the homogeneous dispersion of these fibers and the strong bonding with the matrix as seen in the SEM image. Good bonding is important in composite materials where the load is transferred from the matrix to the reinforcing phase (fibers), increasing the material's compressive strength. Afterward, the compressive strength gradually declines as the volume fraction of these fibers increases. This increase is attributed to the obvious

agglomeration of fibers at high volume fractions due to the difficulty of mixing and heterogeneity of these fibers within the matrix, causing the appearance of some gaps within the structure.

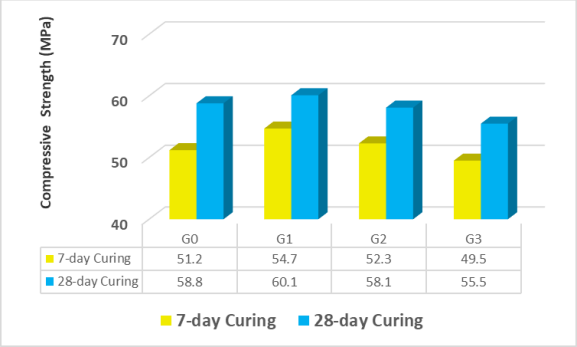


Figure 3. Compressive strength of 20% silica fume modified geopolymer mortar versus different volume fractions of steel fibers at different curing conditions.

5.3. Flexural Strength

The flexural strength test is performed to assess a material's ability to withstand deformation under load. Figure 4 shows the flexural strength values of geopolymer mortar at different curing conditions and different volume fractions of steel fibers. The obtained data exhibited that the flexural strength increased with an increase in the curing time because of the excellent adherence of geopolymer paste to the aggregate particles. Also, it was noticed that the addition of steel fibers leads to a noticeable enhancement in the flexural resistance values, as it increases with increasing the volume fraction of these fibers up to 2vf%.

This improvement in the flexural resistance is due to the role played by these fibers in retarding and preventing the growth of the cracks generated by stresses, thus improving the geopolymer mortar's brittle fracture behavior. With an increase in the volume fraction of steel fibers and at 3vf%, a deterioration in the flexural strength values occurs due to the agglomeration of steel fibers mentioned earlier in Figure 2c.

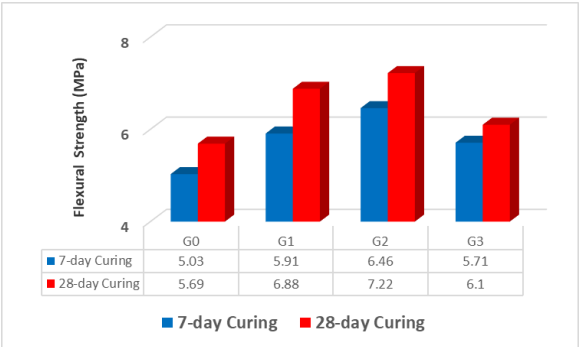


Figure 4. Flexural strength of 20% silica fume modified geopolymer mortar versus different volume fractions of steel fibers at different curing conditions.

5.4. Splitting Tensile Strength

Similar to cement mortar, geopolymer mortar performs very well under compressive loads. The tensile performance of the building materials must also be considered since it affects their capacity to resist cracking.

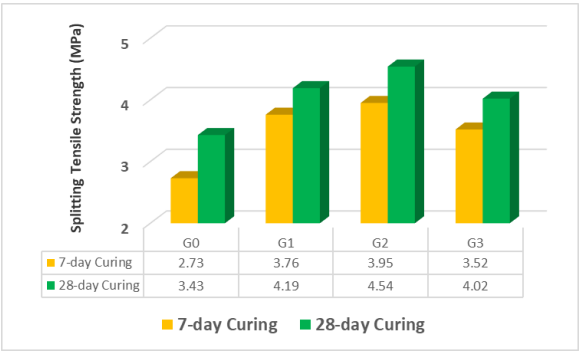


Figure 5. Splitting Tensile Strength of (20%) Silica Fume Modified Geopolymer Mortar versus Different Volume Fraction of Steel Fibers at Different Curing Conditions.

The splitting tensile strength results of all mixtures are shown in Figure 5. The splitting test results showed similar behavior to the flexural test results, where the steel fibers greatly affected the tensile strength values by impeding the growth of cracks and improving the brittle fracture of geopolymer mortar.

5. CONCLUSIONS

This research looked at the relationship between the mechanical features represented by compressive, flexural, and tensile properties and the fracture behavior of GGBS-based geopolymer mortar treated with 20% silica fume. The experimental outcomes demonstrated that adding steel fibers significantly improved the

fracture behavior of geopolymer cement modified with silica fume. Steel fibres are retarding and preventing the growth of the cracks generated by stresses. The results showed a significant improvement in the splitting tensile strength and flexural strength, particularly at 2% of steel fibers. Compressive strength measurements show a minor improvement, notably at 1% steel fibres, and then begin to decline at this volume fraction. Additionally, the curing process is vital in enhancing the geopolymer mortar's mechanical qualities, which become better the longer it cures.

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