Nanotechnology Perceptions
ISSN 1660-6795
www.nano-*ntp.com*

Performance Assessment Of Glass Fiber-Reinforced Geopolymer Mortar Under Diverse Curing Conditions

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In light of growing concerns about the depletion of the ozone layer and global warming, the construction industry is increasingly prioritizing the adoption of eco-friendly building materials. Geopolymer concrete has emerged as a notable focus for researchers and construction professionals, owing to its capacity to utilize waste by-products as an alternative to traditional cement. This innovative approach helps in curbing greenhouse gas emissions during the production process. Geopolymer concrete, a sustainable and revolutionary building material, serves as a substitute for traditional cement concrete. However, geopolymers tend to exhibit quasi-brittle properties, necessitating extensive research dedicated to the advancement, characterization, and practical implementation of fiber-reinforced geopolymers across diverse application domains. This study investigates the integration of glass fibers into geopolymer composites to enhance mechanical properties such as tensile and flexural strength. Geopolymer mortar is developed using fly ash and ground granulated blast furnace slag (GGBS) as binders, eliminating the need for oven curing. Experiments were conducted with varying glass fiber content (0%, 0.5%, 1%, and 1.5% volume fraction) to assess fresh properties (normal consistency, initial and final setting times, and flow value) and mechanical properties (compressive, split tensile, and flexural strength) under both oven and outdoor curing conditions. The ratio of sodium hydroxide to sodium silicate in the alkali activator was fixed at 1.5, and the alkali activator-to-binder ratio was maintained at 0.45. Fresh properties were investigated using various sodium hydroxide concentrations (8 M, 10 M, 12 M, 14 M, and 16 M). For the mechanical strength analysis, a sodium hydroxide concentration of 12 M was selected.

Keywords – Geopolymer mortar; fly ash; glass fiber; ground granulated blast furnace slag (GGBS); mechanical strength; mortar properties

1. Introduction

Presently, cement manufacturing is thought to be a significant source of CO_2 emissions. Researchers everywhere must now give climate change their whole attention as it has become a critical concern. Population increase and growing CO_2 emissions are directly correlated.

Consequently, the environmental damage brought on by CO_2 emissions and cement manufacture has a substantial impact on both cement producers and the general population. Traditional OPC concrete should be replaced with contemporary structural materials to address the issue of sustainable development. The pioneering work in this field dates back to 1978, attributed to Joseph Davidovits, who coined the term "geopolymer" in 1990 to describe this novel class of materials [1]. Geopolymer technology presents an eco-conscious solution by utilizing industrial waste materials such as fly ash and blast furnace slag, rich in alumina and silica, to create a cement alternative for concrete production, as referenced in literature [2], [3], [4], [5]. Geopolymerization occurs when silicon and aluminium oxides from these waste materials react with an alkaline solution, forming a cementitious material without contributing to greenhouse gas emissions [6], [7], [8], [9]. The curing process significantly affects the strength of the geopolymer concrete; specimens cured in an oven exhibit greater compressive strength compared to those cured in an ambient environment [10]. However, the reliance on external thermal curing for fly ash-based geopolymers poses challenges for large-scale industrial implementation, whereas geopolymers based on GGBS (Ground Granulated Blast Furnace Slag) offer an advantage by achieving sufficient strength through ambient curing alone, eliminating the need for external energy sources [9], [11]. This innovation not only mitigates environmental impact but also enhances the viability of geopolymer technology in large-scale applications. GGBS is widely employed in the manufacturing of geopolymer concrete. Its inclusion in fly ash-based geopolymer concrete has proven beneficial for enhancing concrete strength, even at modest proportions [6]. Nevertheless, the extent of its impact is contingent upon various factors, including the activating solution's type and concentration, as well as the ratios of GGBS to fly ash [6], [7]. Research indicates that precursor materials containing higher levels of calcium oxide (CaO) contribute to heightened strength in geopolymer concrete. This, in turn, results in reduced setting time and enhanced mechanical properties when cured under ambient temperature conditions [7].

The cementitious material created using a geopolymer-based binder demonstrates similar properties and appearance to those produced from a binder based on cement [12]. These materials are identified as quasi-brittle, possessing low tensile strength. Consequently, incorporating fibers into the geopolymer system is widely acknowledged as a method to bolster the strength of geopolymer composites [13], [14], [15]. Moreover, according to Sakulich [16], geopolymer composites hold promise for environmental benefits over conventional cement, and their ductility and durability can be enhanced through fiber reinforcement. This implies that geopolymer composites could offer both improved mechanical properties and greater environmental friendliness compared to traditional cement-based materials. Numerous research studies have shown that incorporating various synthetic fibers can significantly enhance the mechanical properties of fly ash-based geopolymer composites. The fibers studied include basalt, steel, polyethylene, polyvinyl alcohol (PVA), polypropylene (PP), polyolefin, glass, and carbon fibers. These fibers have been found to markedly improve the flexural strength and splitting tensile strength of the composites. Specifically, basalt fibers contribute to thermal and chemical resistance, steel fibers provide superior crack resistance and load-bearing capacity, and polyethylene fibers enhance ductility and toughness [17], [18], [19]. Polyvinyl alcohol fibers improve tensile properties and crack resistance [20] while polypropylene fibers reduce shrinkage and enhance impact resistance [21], [22], [23]. Glass

fibers enhance structural integrity and dimensional stability [24], [25], and carbon fibers provide exceptional strength and stiffness, significantly improving tensile and flexural properties. The effective interfacial bonding between these fibers and the geopolymer matrix ensures efficient stress transfer, preventing fiber pull-out and enhancing load distribution. The result is geopolymer composites with superior mechanical properties, improved durability, and enhanced performance in various structural applications [26], [27], [28].

It is seen that, integrating glass fibers into geopolymer composite displays promise for enhancing its mechanical attributes, including tensile and flexural strength. Glass fibers, in particular, have undergone thorough examination for their potential application in reinforcing geopolymer mortar. However, further investigation is required to fine-tune the fiber content for optimal performance. The study will conduct experiments involving varying levels of glass fiber content in geopolymer mortar specimens. These experiments will analyze the fresh properties, including initial and final setting times, with various blends of GGBS and fly ash, as well as the workability of geopolymer mortar with different percentages of added glass fiber. Additionally, the mechanical characteristics, such as compressive strength, split tensile strength, and flexural strength, will be assessed. The findings from these experiments will be scrutinized to determine the optimal glass fiber content for enhancing the performance of geopolymer mortar. In addition to that, due to the significant issue of heat curing in the development of geopolymers, outdoor curing has been attempted in this work as a means of avoiding heat curing.

2. Materials and Methods

2.1 Materials

The experimental program utilized fly ash sourced from the NSPCL Bhilai, Chhattisgarh, India, which is classified as class F fly ash, confirmed IS 3812-2013 (part-II) [29]. The specific gravity of fly ash, found to be 2.28 confirms IS 1727 [30]. The fineness of fly ash is 280 m^2/kg. GGBS was acquired from Bellary, Karnataka's Jindal Steel Works (JSW). The specific gravity of GGBS is 2.88 and the fineness of GGBS is found to be 375 m^2/kg. The chemical composition using X-ray Fluorescence of binder materials is shown in Table 1. In this study, natural river sand that was readily accessible locally was utilized as the fine aggregate, and it was sieved using a 2.36 mm sieve. According to IS 383-2016 [31], sand is classified as Zone-II since its specific gravity is 2.7 and its fineness modulus is 2.75. The alkaline activator (AA) commonly employed consisted of a mixture of sodium hydroxide (SH) and sodium silicate (SS) solution, obtained from local manufacturers. To prepare the alkaline liquids, sodium hydroxide flakes with 98% purity were used, along with liquid sodium silicate - Na_2O-14.70%, SiO_2-34.26% and H_2O - 51.04%. Alkali-resistant glass fiber obtained from Swastic International, Gujarat, was used, with a bulk density of 2680 kg/m3. The length of the glass fiber used in this research is 24 mm with an average diameter of 14 μm. Superplasticizer CONPLAST SP-430, based on sulfonated naphthalene and supplied by Fosroc Chemicals, India, was employed. It comes in a dark solution that quickly dissolves in an alkaline solution and is free of chlorides. The raw materials used in this research work are shown in Figure 1.

Figure 1. (a) Fly ash, (b) GGBS, (c) glass fiber (d) SH flakes and (e) SS

Table 1. Chemical Composition of binding materials using X-ray fluorescence (wt. %)

Chemical Composition	Fly Ash (class F)	GGBS
CaO	4.5	37.63
SiO_2	56.42	34.81
Al_2O_3	25.92	17.92
Fe_2O_3	4.2	0.66
MgO	1.72	7.8
SO_3	0.39	0.2
Na_2O	0.18	NIL
MnO	NIL	0.21
LOI	0.76	NIL

2.2 Experimental Program

2.2.1 Mixture Proportioning

In the formulation of Geopolymer mortar, several materials are proportioned to achieve desired properties. This includes a combination of fly ash and GGBS (Ground Granulated Blast Furnace Slag) serving as binders, determining the binder to sand ratio, alkali activator to binder ratio, and the ratios of (SS) to (SH). In this specific study, the alkali activator to binder ratio is set at 0.45, while the SS to SH ratio is fixed at 1.5 with varying concentrations of SH at 8, 10, 12, 14, and 16 moles. Additionally, the effect of glass fiber reinforcement is examined by adding alkali-resistant glass fiber at volume fractions of 0%, 0.5%, 1.0%, and 1.5% to the geopolymer mortar. To analyze different strengths, the concentration of SH is maintained at 12 moles, with all other parameters kept constant. The mixture proportions of geopolymer mortars are detailed in Table 2, with mixtures named to reflect their composition, such as F85G15GF1.0, indicating 85% fly ash, 15% GGBS, and 1.0% glass fiber. This systematic approach allows for the examination of various mixtures and their resulting properties.

2.2.2 Casting and Curing

A concentration of 12 molarities was achieved by distilling 480 grams of SH in 1 liter of water, respectively. To prepare the alkali activator, first, SH flakes are added to water to achieve the desired concentration. After the SS solution cools down, SS is then directly added to it. This entire process must be done 1 day before conducting the experiment. Binder and sand were mixed for 5 minutes until a homogeneous mixture was obtained. Then, the alkali activator was added and mixed manually for 10 minutes. Finally, glass fiber was added and mixed again for 2 minutes. After this, a 70.6×70.6×70.6 mm^3 cube for compressive strength test, a 100 mm diameter and 200 mm height cylinder for split tensile strength test, and 40×40×160 mm^3 molds for flexural strength test are used for casting. An electric table vibrator is used for compacting mortar cubes. The samples are demolded after 24 hours and kept for hot oven and outdoor curing. For hot oven curing, the samples are kept for 24 hours at 60 ℃ and then at room temperature till testing. Samples designated for outdoor curing are maintained at room temperature until the time of testing. The outdoor-cured samples and hot oven-cured samples are shown in Figures 2 and 3, respectively. The average of all test results of 3 samples has been taken. In this study, the normal consistency of the geopolymer material has been determined in the same way as for cement as per IS 4031 (Part-IV) [30]. The normal consistency achieved is denoted by "P". Initial setting time and final setting time of geopolymer material are determined according to IS 4031 (Part-V) [31] in which the geopolymer matrix is made with 0.85P, an alkaline activator solution. As specified by ASTM C1437 2007 [32], the flow value of mortar is calculated.

Table 2. Mixture Proportion

S. No.	Mix Designation	Fly Ash (kg/m^3)	GGBS (kg/m^3)	Sand (kg/m^3)	SH (kg/m^3)	SS (kg/m^3)	AA Solution (kg/m^3)	GF (kg/m^3)
1	F100G0GF0	700	-	1400	126	189	315	-
2	F100G0GF0.5	700	-	1400	126	189	315	13.4

3	F100G0GF1.0	700	-	1400	126	189	315	26.8
4	F100G0GF1.5	700	-	1400	126	189	315	40.2
5	F85G15GF0	595	105	1400	126	189	315	-
6	F85G15GF0.5	595	105	1400	126	189	315	13.4
7	F85G15GF1.0	595	105	1400	126	189	315	26.8
8	F85G15GF1.5	595	105	1400	126	189	315	40.2
9	F75G25GF0	525	175	1400	126	189	315	-
10	F75G25GF0.5	525	175	1400	126	189	315	13.4
11	F75G25GF1.0	525	175	1400	126	189	315	26.8
12	F75G25GF1.5	525	175	1400	126	189	315	40.2
13	F65G35GF0	455	245	1400	126	189	315	-
14	F65G35GF0.5	455	245	1400	126	189	315	13.4
15	F65G35GF1.0	455	245	1400	126	189	315	26.8
16	F65G35GF1.5	455	245	1400	126	189	315	40.2
17	F50G50GF0	350	350	1400	126	189	315	-
18	F50G50GF0.5	350	350	1400	126	189	315	13.4
19	F50G50GF1.0	350	350	1400	126	189	315	26.8
20	F50G50GF1.5	350	350	1400	126	189	315	40.2

Figure 2. Outdoor-cured Mortar cubes

Figure 3. Mortar cubes under oven curing

3. Results and discussion

3.1 Fresh Properties of Geopolymer Paste

3.1.1 Normal Consistency

To study the normal consistency of the geopolymer paste, different combinations of fly ash and GGBS are examined with different concentrations of SH. It is observed from Figure 4 that the normal consistency is increased by increasing the GGBS content. Maximum normal consistency of 38% is observed at the combination of 50% fly ash and 50% GGBS. When fly ash was substituted with up to 50% GGBS, the normal consistency exhibited a respective increment of 26.67%, 16.67%, 13.33%, 12.5%, and 9% for 8, 10, 12, 14, and 16 molar concentrations, respectively. The range of normal consistency is seen to be 30-38 minutes. There is not much effect on the normal consistency by increasing the concentration of SH, and a similar pattern is noted by G. Mallikarjuna Rao [33].

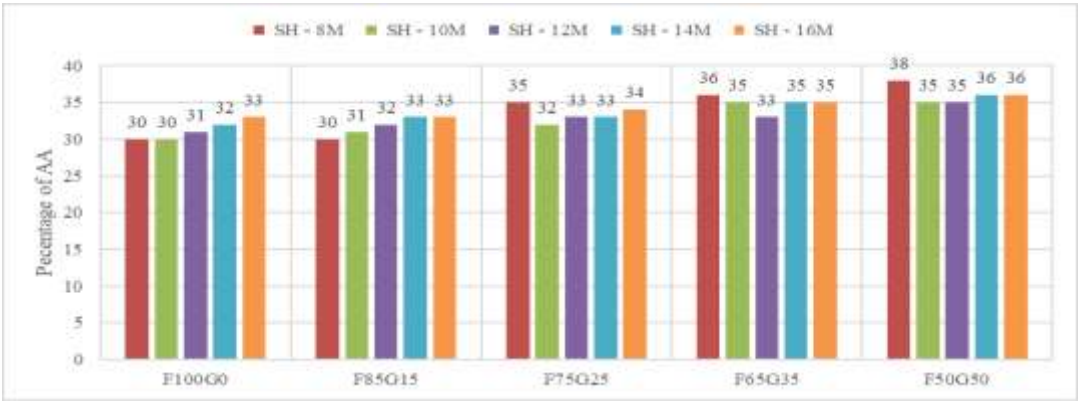

Figure 4. Normal Consistency of geopolymer paste for different concentrations of SH

3.1.2 Setting Time

Initial and final setting time are represented in Figure 5 and 6, respectively. When observed different combinations of fly ash and GGBS with different molar values of SH, it was found that on increasing the molarity of SH, the initial setting time and final setting time both are increased while on increasing the percentage of GGBS, the initial setting time and final setting time both are decreased the similar trend is observed by [33-35]. From the table provided, it's evident that as the concentration of SH in the alkali activator solution increases, the initial setting time and final setting time generally increase across all mix combinations. This trend suggests that higher concentrations of SH lead to longer final setting times in the mixture. Additionally, for a given concentration of SH, the initial setting time and final setting time tend to decrease as the proportion of GGBS increases in the mix combination. This implies that a higher percentage of GGBS promotes faster setting times. The variation of the initial setting time in different combinations was observed from 35 to 125 minutes, and the final setting time from 100 to 320 minutes.

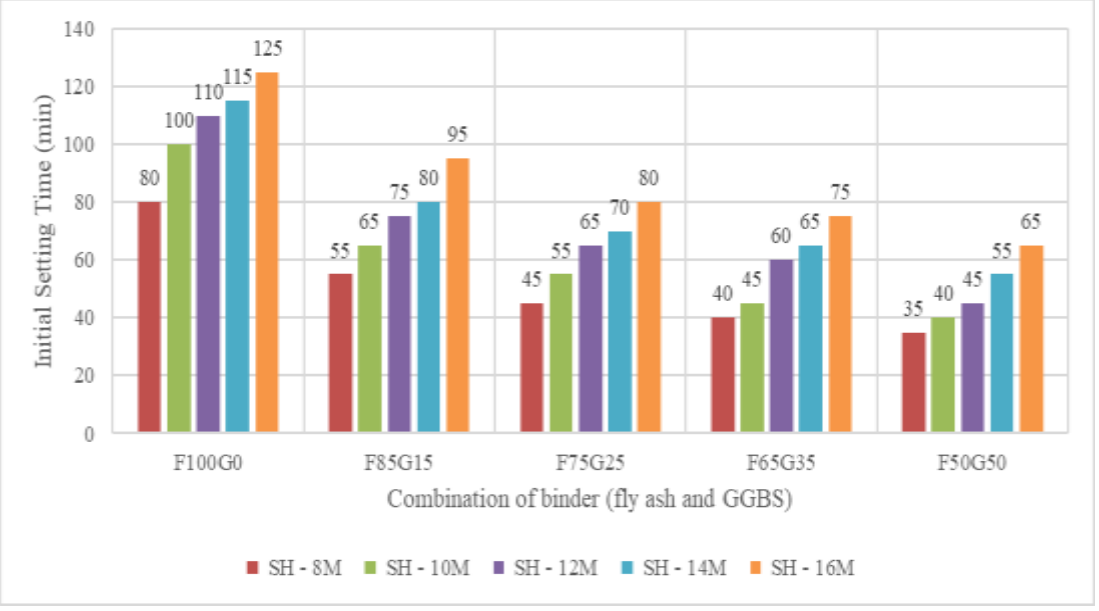

Figure 5. Initial setting time of geopolymer paste for different concentration of SH

Figure 6. Final setting time of geopolymer paste for different concentrations of SH

3.1.3 Flow Value

To analyze the flow values of geopolymer mortar with various fly ash and GGBS combinations, a sulfonated naphthalene-based superplasticizer is incorporated at 4% by binder weight. Figure 7 represents the flow values of geopolymer paste, revealing that as the sodium hydroxide (SH) concentration increases, the flow values decrease. Furthermore, increasing the proportion of GGBS in place of fly ash leads to further reductions in flow values; the same trend was observed by [36]. When 100% fly ash is utilized as the binder, flow values range from 135% to 96% as SH concentration varies from 8 moles to 16 moles. Conversely, substituting fly ash with GGBS in various proportions results in a decrease in flow value from 135% to 118% at an 8-moles SH concentration. This phenomenon can be attributed to the differing particle characteristics; fly ash particles are spherical and facilitate easy movement, whereas GGBS particles have a rough, flaky, and elongated morphology, leading to higher internal friction compared to the smoother fly ash particles.

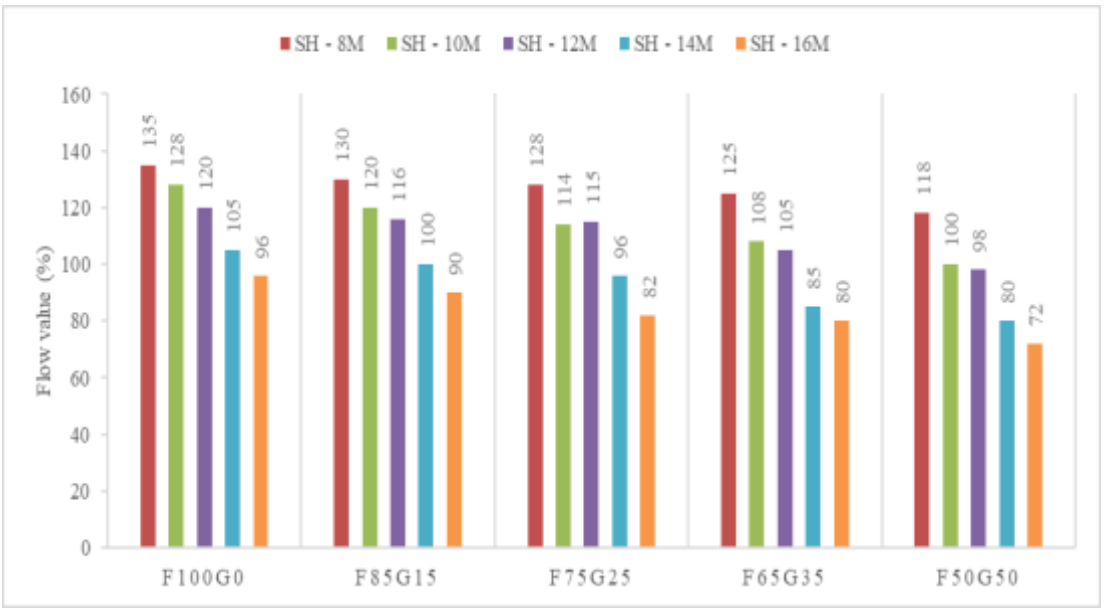

Figure 7. Flow value of geopolymer paste in different combinations of fly ash and GGBS

It can be seen that the flow value of geopolymer mortar decreases due to the addition of glass [37]. When glass fiber content varied from 0 to 1.5% is added to the 50% fly ash and 50% GGBS binder combination, the flow value ranged from 118% to 35% for the 8 moles SH concentration. The test results revealed that for all combinations with the addition of glass fiber, the flow value varied from 135% to 30%.

3.2 Hardened Properties of Geopolymer Mortar

To investigate the various strengths of geopolymer mortar, the concentration of SH was fixed at 12 moles, and the remaining parameters were kept as is. Compressive strength, split tensile strength, and flexural strength are investigated by oven curing and outdoor curing, which have been discussed earlier.

3.2.1 Compressive Strength of Geopolymer Mortar

Figure 8 shows the compressive strength of geopolymer mortar with glass fiber for the SH concentration of 12 moles under oven curing and outdoor curing. In the oven curing condition, the range of compressive strength was observed to be from 25.4 MPa to 34.5 MPa, and in the outdoor curing condition, this range was from 21.1 MPa to 28.1 MPa. These results indicate that the geopolymer can achieve strength even under outdoor curing conditions if GGBS is mixed with fly ash. When a combination of 100% fly ash, 0% GGBS, and 0% glass fiber is used, the compressive strength of oven-dry cured mortar was 28.1 MPa, and that of outdoor cured mortar was 23.3 MPa, which is 17% less than compared of oven-dry cured. It is also observed that when fly ash is replaced by GGBS up to 50%, there is up to a 22% increase in

compressive strength without glass fiber for oven-cured samples and a 19.7% increase for outdoor-cured samples. When glass fiber is added to the mortar, no significant increase in compressive strength is seen. In all combinations, it was noticed that maximum compressive strength was achieved at 0.5% glass fiber volume fraction, a similar trend is found by [37]. For the combination of 50% fly ash, 50% GGBS, and 0.5% glass fiber content, maximum compressive strength is achieved for both curing conditions.

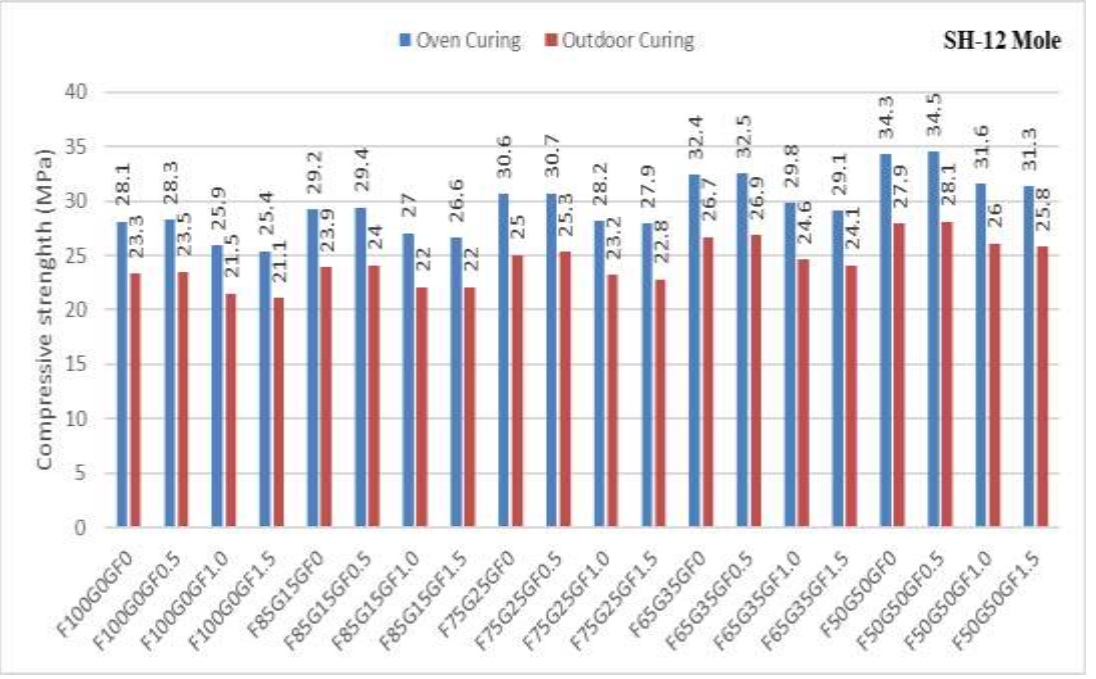

Figure 8. Compressive strength of geopolymer mortar with the addition of glass fiber

3.2.2 Split Tensile Strength of Geopolymer Mortar

Figure 9 represents the split tensile strength of geopolymer mortar reinforced with glass fiber. Split tensile strength range was found to be 1.8 MPa to 2.7 MPa for oven curing conditions and 1.5 MPa to 2.2 MPa for outdoor curing conditions. When fly ash was replaced from 0% to 50% by GGBS without adding glass fiber, the split tensile strength value in the range of 1.8–2.5 MPa was obtained, and thus an increase of up to 38.9% was observed for oven cured samples and for outdoor cured samples it ranges 1.5-1.8 MPa. It was also observed that the split tensile strength of outdoor cured samples was less than that of oven cured samples. For the combination of F100G0GF0, the split tensile strength for oven-cured samples and outdoor-cured samples is 1.8 and 1.5 MPa, respectively, which is 16.67% less. Furthermore, the combination of F50G50GF0, the split tensile strength for oven-cured and outdoor-cured samples is 2.3 and 1.8 MPa, respectively, which is 21.74% less. When glass fiber is added, the split tensile strength of oven-cured samples is seen to be in the range of 1.8–2.7 MPa (50% increment), and that of outdoor-cured samples is seen to be in the range of 1.5–2.2 MPa

(46.67% increment). Maximum split tensile strength was obtained at 1% glass fiber content for all the combinations and both curing conditions. The split tensile strength for the combination of F100G0GF0 is 1.8 and for F100G0GF1.0 is 2.3 MPa for the oven-cured sample; hence, in this condition, split tensile strength is increased by 27.78%. Similar results are found by fiber [37].

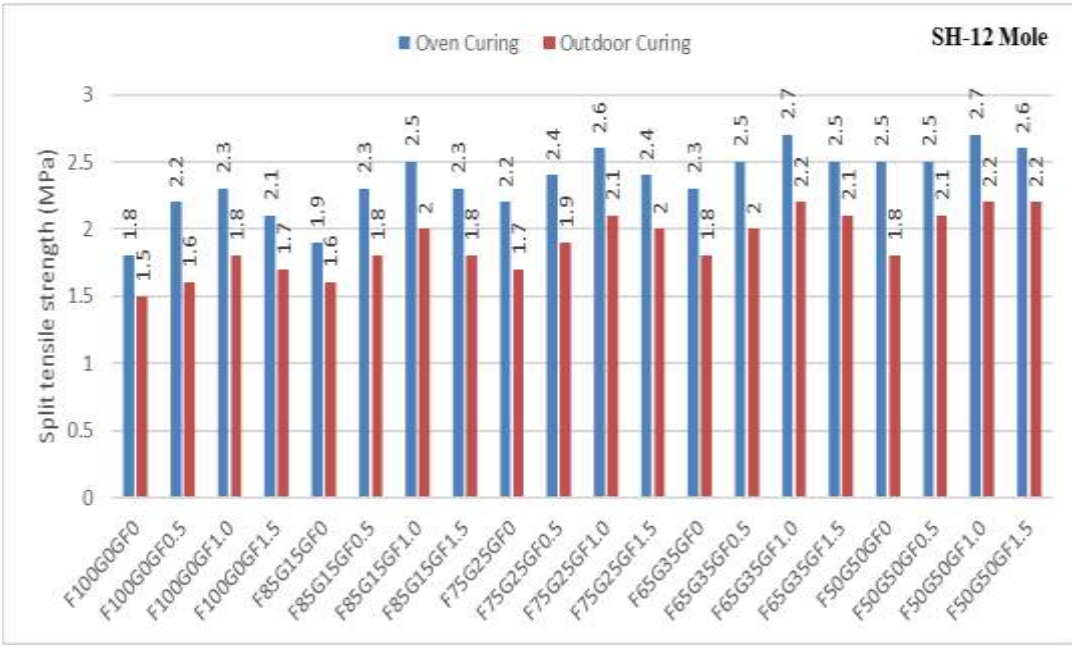

Figure 9. Split Tensile strength of geopolymer mortar with the addition of glass fiber

3.2.3 Flexural Strength of Geopolymer Mortar

Flexural strength is represented in Figure 10. For the combinations F100G0GF0, 85G15GF0, F75G25GF0, F65G35GF0, and F50G50GF0, the flexural strength was observed at 2.9, 3.1, 3.2, 3.3, and 3.5 MPa for oven curing conditions and 2.4, 2.4, 2.5, 2.7, and 2.8 MPa for outdoor curing conditions, respectively. By increasing the percentage of GGBS, an increase in flexural strength was observed. The flexural strength varies 2.9 to 4.4 MPa for oven curing conditions and 2.4 to 3.5 MPa for outdoor curing conditions. Flexural strength is maximum at 1% glass fiber content for both curing conditions. The same trend is found by [37]. When glass fiber is added, the flexural strength for the combination of F65G35GF1.0 is increased by 27.27% when compared to F65G35GF0 for oven curing conditions and 25.92% for outdoor curing conditions.

The experimental results indicate that the compressive strength of geopolymer matrices is significantly enhanced when fly ash is partially or entirely substituted with GGBS. This enhancement is attributed to the presence of calcium oxide (CaO) in GGBS, which contributes

to the geopolymerization process. Additionally, the geopolymer exhibits the capacity to effectively cure under ambient outdoor conditions, obviating the need for thermal curing processes. When fly ash and GGBS are utilized as the primary source materials, the geopolymer achieves the desired mechanical properties without the requirement for oven curing. The incorporation of glass fibers into the geopolymer matrix results in a substantial increase in both split tensile strength and flexural strength. While geopolymer mortar is inherently brittle, its ductility can be significantly improved through the addition of glass fibers.

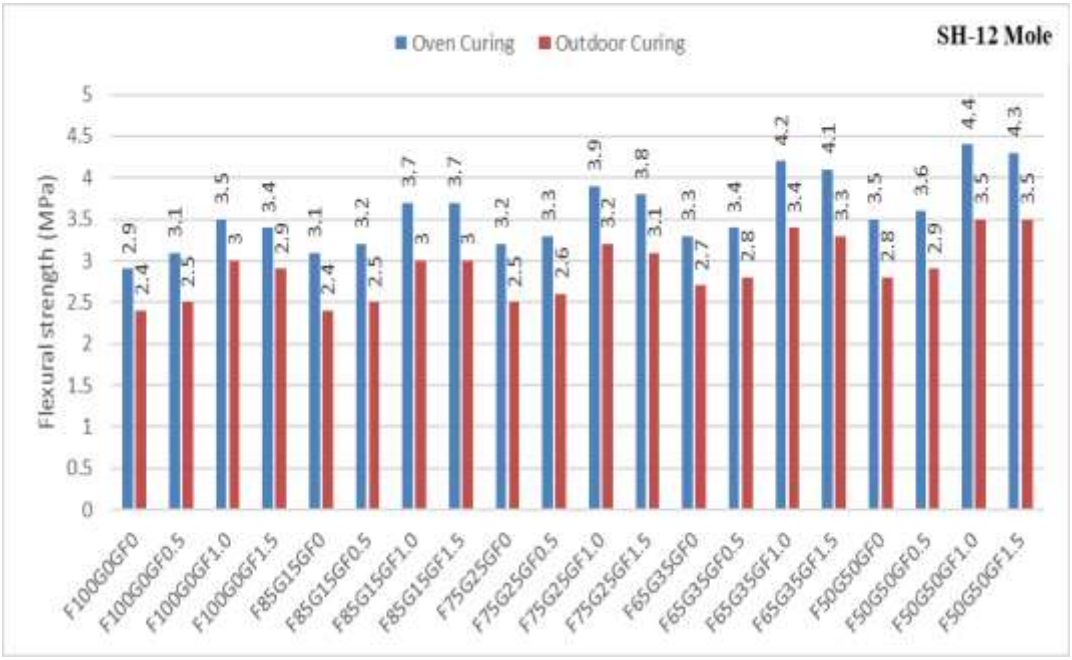

Figure 10. Flexural strength of geopolymer mortar with the addition of glass fiber

4. Conclusion

In this paper, the fresh properties and mechanical properties of fly ash-GGBS blend geopolymer mortar were studied with and without glass fiber under oven curing and outdoor curing conditions, on the basis of which the following conclusions were obtained:

- As the percentage of GGBS increases, the normal consistency also increases correspondingly. At a 50% substitution level of GGBS, the maximum increase in normal consistency is observed at 26.67%. In contrast, variations in sodium hydroxide concentration have a minimal effect on normal consistency.

- Increasing the percentage of GGBS resulted in a decrease in the initial setting time. Conversely, an increase in the concentration of sodium hydroxide led to an increase in the initial setting time.

- The final setting time decreased with higher GGBS content, while it increased with rising sodium hydroxide concentration.

- An increase in GGBS content, sodium hydroxide concentration, and glass fiber volume fraction led to a reduction in the flow value. Therefore, incorporating a superplasticizer is essential to enhance the workability of the geopolymer paste.

- Compressive strength showed a progressive increase with higher levels of GGBS replacing fly ash under both oven-curing and outdoor-curing conditions. The maximum compressive strength was achieved at a glass fiber volume fraction of 0.5% for both curing methods.

- Split tensile strength and flexural strength also improved with increasing GGBS content. The highest values for both parameters were recorded at a glass fiber volume fraction of 1% under both curing conditions.

- Results from outdoor curing indicate that geopolymer mortar incorporating GGBS and fly ash can achieve satisfactory performance without the need for oven curing, supporting the feasibility of ambient-cured systems.

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