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Influence of Steel and Poly Vinyl Alcohol Fibers on the Development of High-Strength Geopolymer Concrete

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Abstract: The present study focuses on the mechanical performance of steel and polyvinyl alcohol fibers embedded in the geopolymer matrix. A high-strength geopolymer concrete with fly ash, slag and silica fume as precursors and sodium hydroxide and sodium silicate solutions as activators has been tested for its strength in compression and flexure. The influence of fibers on flowability, long-term shrinkage and sulphuric acid attack on the geopolymer concrete has also been studied. The dosage of fibers was maintained at 1%, 2% and 3% by volume, and fibers of length 13 mm have been used in the study. Results indicate that slag with 3% steel fibers by volume had a predominant influence on the strength development of steel fiber-reinforced geopolymer concrete, yielding a compressive strength of 107 MPa after 28 days. Blast furnace slag resulted in increasing the shrinkage of concrete due to rapid gel formation owing to the presence of calcium ions, although the fibers helped reduce the shrinkage to some extent. The strength of steel fiber geopolymer concrete was superior to PVA fiber geopolymer concrete; however, after an acid attack, the strength of steel fiber geopolymer concrete was reduced more than PVA fiber geopolymer concrete due to the enhanced corrosion resistance of PVA fibers.

Keywords: steel fiber geopolymer; PVA fiber geopolymer; shrinkage; acid resistance; ambient curing



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1. Introduction

The development of high-strength concrete has become increasingly essential in the construction industry, particularly for applications requiring superior mechanical performance and durability. High-strength concrete is a cement-based composite with superior performance in terms of its strength-to-weight ratio and durability aspects [1–4]. As per ACI 363 [5], concrete with a strength exceeding 8000 psi (55 MPa) can be termed as high-strength concrete. These concrete mixes, after hardening, are used in civil engineering applications such as the construction of high-rise buildings, bridges with high spans, pre-stressed concrete structures and blast-resistant structures [6–8]. The strength of a hardened concrete or mortar mix is directly proportional to the cement content of the mix, and to achieve ultra-high strengths, usually, a cement content of more than 30% weight of the mix is used, which amounts to three times what is being used in conventional cement concrete mixes [9–11]. Even with the partial replacement of cement with supplementary cementitious material like silica fume, fly ash or blast furnace slag, the amount of cement used for high-strength mixes is still very large, leading to a severe carbon footprint during the production phase. The energy required to produce clinker is 3600–4000 MJ/ton, and the associated CO₂ emissions are in the range of 800–950 kg/ton [12,13].

Supplementary cementitious materials with pozzolanic properties, such as Fly ash and blast furnace slag, are used as partial replacement of cement for the production of Portland

Pozzolana cement. The energy required and the CO₂ emitted are relatively lesser and are in the range of 2700–3000 MJ/ton and 600 kg/ton, respectively [12]. With the amount of supplementary cementitious materials usage in cement being limited due to the strength and durability constraints, alkali activation and geopolymerization are an alternative and more viable approach in using these industrial wastes/by-products as resource material in producing a clinker-free binder [14,15].

Widely regarded as a green initiative, geopolymer concrete is an inorganic polymer prepared by activating resources that are abundant in aluminosilicates such as fly ash from the coal industry, blast furnace slag from the steel industry and metakaolin which is kaolinite heated to 600 °C [16–21]. These aluminosilicate resources are activated using alkali hydroxides, silicates, carbonates and sulphates [22]. The most widely used activators are sodium hydroxide and sodium silicate [23–26]. The chemistry of geopolymerization is based on three steps, namely, nucleation, coagulation and crystallization. Dissolution of alumina, silica and calcium ions from the precursors, mostly fly ash (Class C or Class F), slag, metakaolin, silica fume, etc., in a high-pH medium (activators) constitute nucleation. In the next step, during coagulation, the released silicon (Si) and aluminum (Al) ions undergo polycondensation reactions, forming a three-dimensional polymeric network with oxygen bridges linking Si-O-Si, Al-O-Al and Al-O-Si bonds. The polymeric network then solidifies into a gel-like structure, providing geopolymers with strength, durability and hardening over time, leading to crystallization. Based on the precursor, a combination of sodium aluminum silicate hydrates (N-A-S-H) and calcium aluminum silicate hydrates (C-A-S-H) are formed [27,28]. Strictly speaking, flyash based precursors produce N-A-S-H and are mostly termed geopolymers for their complete and more stable 3D network, whereas the precursors that involve slag form C-A-S-H along with N-A-S-H and are mere alkali-activated materials [27,29]. Nonetheless, these two terms are most often used interchangeably.

Flyash based geopolymers underperform in mechanical strength when cured at ambient room temperature and require high-temperature curing to achieve optimum strength [30,31]. Slag-based geopolymers attain high strength even at room temperature due to the presence of calcium ions acting as nucleation sites.

Existing approaches for making design mix proportions for high-strength geopolymer concrete can be classified into three steps: target strength approach, performance-based design and statistical factorial model [32]. The target strength approach refers to optimizing the water-binder ratios or alkaline liquid-binder ratios and the ratio of coarse and fine aggregates. Performance-based design is more subtle in its approach as it employs both strength and durability in designing the mix proportions. The statistical model approach employs a sensitive analysis to identify the influencing factors on geopolymer concrete characteristics. These factors in geopolymer concrete can be alkaline content and precursor composition.

There are various ways to produce a high-strength geopolymer, but three are more prominent than the rest. The first way is by increasing the concentration of the activators; the increased molarity of the alkaline solution enables a faster dissolution of aluminosilicate species, yielding better strength. The second way is to use more than one precursor, especially using an amorphous silica source or reactive calcium-based source. The third way is to use fibers as a reinforcement in concrete to enhance its strength. The most commonly used fibers are steel, Poly Vinyl Alcohol (PVA), basalt and carbon fibers.

The primary purpose of the fibers is to enhance the mechanical properties and avoid brittle failure of geopolymer concrete. Fiber-reinforced concrete displays strain hardening features upon breaking and have higher densities. Additionally, the fibers have the ability to enhance the geopolymer's absorption of energy prior to the development of damage. They also limit the width of cracks and lower both their dimension and size. It is important to remember that natural fiber reinforcements have poorer mechanical strengths, which often prevents them from being used in the intended methods [33]. Compared to natural fibers, inorganic fibers often display stronger mechanical strengths, allowing for the creation of homogenous materials [34].

Huang et al. deduced that as much as 1.5% by volume of steel fibers increased the flexural strength energy by 31% [35]. Also, geopolymer concrete developed by using fly ash, slag and silica fumes as precursors with steel fibers has increased the compressive strength from 124 MPa to 175 MPa [36]. Polyvinyl alcohol and polyethylene fibers, too, have been reported to have increased the load-bearing and energy absorption capacities of concrete to a significant extent [37]. Increasing the dosage of steel fibers has been reported to have reduced the mean space between fibers and facilitated better bonds between the matrix and the fibers, leading to the suppression of crack propagation [38]. Also, the length of steel fibers has been reported to have had an impact on the strength evolution of concrete. A hybrid concrete made of steel fibers and basalt fibers demonstrated an increase in projective impact resistance of the composite when compared to a composite made only out of steel fiber [39].

Blast furnace slag and silica fume have been reported to have been used in most studies related to high-strength geopolymer concrete: blast furnace slag for its potential to achieve high strengths at an ambient curing temperature due to the presence of calcium ions and silica fume for its amorphous form of silica for geopolymerization reaction. A silica fume dosage of 12.5% was observed to be optimum for workability, and the mix yielded a compressive strength of 178.6 MPa [40]. In a separate study, a silica fume dosage of 30% has been reported to have increased the fracture energy by around 49.7% [41]. Geopolymer composite made of 78% blast furnace slag along with 5% silica fume with 3% steel fiber by volume when steam-cured for 24 h and subsequently cured in water for 28 days yielded a compressive strength of 156 MPa [42].

Most studies focused on the strength development of the geopolymer concrete, shrinkage and durability properties of concrete have hardly been evaluated. The present work evaluated the long-term shrinkage of the geopolymer concrete for up to one year and the influence of acid attack on the strength of fiber-reinforced geopolymer concrete along with its mechanical performance. Also, the study is an effort to develop a geopolymer mix that could achieve high strength even when cured at ambient room temperature.

2. Materials and Methods

For the present study, three sources of aluminosilicate wastes/by-products were used as precursors. Blast furnace slag, fly ash (Class F) and silica fume were used as precursors, and liquid sodium hydroxide and liquid sodium silicate were used as activators. Slag typically had a more angular morphology with a rough surface, which enhances mechanical interlocking and promotes better bonding within the geopolymer matrix. Fly ash, on the other hand, was spherical with a smoother texture, contributing to workability and flowability. Silica, particularly in amorphous form, contributes to increased reactivity due to its high surface area and fine particle size, enhancing geopolymerization. The dryness of the raw materials were ensured before geopolymer preparation. Fly ash was procured from Salt River Materials Group, Arizona, and blast furnace slag had been procured from a local vendor, River City Ready Mix, Ruston, Louisiana. The silica fume used in the study was Microsilica and sourced from Sika, United States. The chemical composition and physical properties of the precursors are listed in Table 1. The sodium hydroxide solution contained 50% by weight, with a specific gravity of 1.51 and a pH of 14. Liquid sodium silicate, which consists of soda (Na_2O) and silica (SiO_2) dissolved in water, has SiO_2 and Na_2O contents of 28.7% and 8.9% by weight, respectively, resulting in a weight ratio of 3.22. The sodium silicate solution has a density of 1.38 g/cm³ and a viscosity of 180 cps.

The study also used masonry sand, quartz sand (2.36 mm) and quartz powder as fine aggregates in the geopolymer concrete. Two types of fibers, steel and Poly Vinyl Alcohol (PVA), whose properties are listed in Table 2, had been used in the present study. Fibers of lengths 13 mm in dosages of 1%, 2% and 3% by volume have been adopted. The detailed design mix proportions of the materials used in the study are tabulated in Table 3.

Table 1. Properties of precursors of geopolymer concrete.

Precursor	Chemical Composition (%)						Physical Properties	
	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	LOI (%)	Specific Gravity
Fly ash	2.10	61.70	24.60	4.38	1.22	0.18	0.29	2.27
Silica fume	0.70	91.03	0.19	1.16	2.21	0.95	4.09	2.23
Blast furnace slag	41.41	34.20	13.68	0.75	6.24	1.28	1.20	2.95

Table 2. Properties of fibers used in the study.

Property	Steel Fiber	PVA Fiber
Length	13 mm	13 mm
Thickness	200 µm	40 µm
Tensile Strength	2000 MPa	1600 MPa
Density	7850 kg/m ³	1300 kg/m ³

Table 3. Design mix proportions used in the study (%).

Mix	Blast Furnace Slag	Silica Fume	Fly Ash	Masonry Sand	Quartz Sand	Quartz Powder	Sodium Hydroxide	Sodium Silicate
HS1	39.2	0	0	39.2	0	0	6.1	15.5
HS2	33.32	5.88	0	39.2	0	0	6.1	15.5
HS3	33.32	5.88	0	19.6	9.8	9.8	6.1	15.5
HS4	31.36	7.84	20	39.2	0	0	6.1	15.5

In each of the mixes mentioned in Table 3, steel fibers and PVA fibers had been added by 1%, 2% and 3% volume. Twenty-four mixes, twelve with steel fibers and twelve with PVA fibers, have been used in the present study. The amount (weight) of fibers used in each of the mixes is tabulated in Table 4.

Table 4. Amount (weight) of fibers used in the study (g).

Percentage Volume	Steel Fibers	PVA Fibers
1%	78.5	13
2%	157	26
3%	235.5	39

All the mix notations with fibers incorporated in the geopolymer matrix adopted in the study pertain to four mixes mentioned in Table 3. The geopolymer concrete with 1%, 2% and 3% steel fibers mixed in Mix HS1 is denoted by HS1S1, HS1S2 and HS1S3, respectively. Similarly, geopolymer concrete with 1%, 2% and 3% PVA fibers mixed in Mix HS1 is denoted by HS1P1, HS1P2 and HS1P3, respectively. Similar notations had been adopted throughout all mixes. For example, mix notation HS3P2 represents 2% PVA fibers added to geopolymer mix HS3 from Table 3.

During mixing of geopolymer concrete, the precursors were first blended, and fine aggregate was added to it. The dry mix was mixed for 2 min, following which the liquid activators were poured into the dry ingredients and mixed for 3 min. Finally, fibers were distributed randomly into the paste and mixed for 1 min. A homogenous dispersion of fibers was visually assessed. The mix was then poured into their respective molds and cured at ambient room temperature.

Fresh geopolymer mortar was tested for flowability as representation of increase in average base diameter of the mortar, expressed as a percentage of the original base diameter as per testing provisions mentioned in ASTM C1437 [43]. The test involves mixing

geopolymer paste or mortar to a specified consistency and then placing it into a flow table mold. The mold is filled in two layers, each tamped 20 times. After removing the mold, the table was dropped 25 times within 15 s. The flowability of the paste or mortar was measured by averaging the diameters of the spread mass.

The uniaxial compressive strength tests were performed on geopolymer cubes of size 50 mm × 50 mm × 50 mm after 7 and 28 days of ambient curing temperature. The mix was placed into cube molds, compacted and cured for a set duration. After curing, the cubes were removed, and their compressive strength was tested using a 500,000 lbf capacity automatic compression machine from Glison Company Inc. (Lewis Center, OH, USA) by applying a load until failure at the rate of 200 to 400 lbf/s as per ASTM C109 [44]. To minimize the experimental error, an average value of three specimens was considered. In order to measure the flexural strength of the geopolymer concrete, beams of size 40 mm × 40 mm × 160 mm have been used. The flexural strength of the specimens was measured after 28 days of curing by placing the specimen on a testing machine with supports spaced 100 mm apart. A loading rate of 11.2 lbf/s has been applied using the same compression testing machine at the center of the specimen until failure, as per ASTM C348 [45]. The flexural strength has been calculated by the formula given below in Equation (1).

$$R = \frac{3PL}{2bd^2} \quad (1)$$

where R is the flexural strength;

P is maximum applied load;

L is span between supports;

b is width of the specimen;

d is depth of the specimen.

The durability of geopolymer concrete was evaluated by acid attack tests and the measurements of long-term shrinkage. The geopolymer specimens, after their 28 days of ambient curing, were saturated in 5% sulphuric acid for 90 days and tested for their strength in compression as per ASTM C 267 [46]. The long-term shrinkage of geopolymer specimens was measured as per ASTM C311 [47] for all the mixes with 3% fibers by volume and compared to mixes without any fibers in them. The geopolymer mortar was placed into a prismatic mold of size 25 mm × 25 mm × 285 mm with embedded studs for length measurement. After initial curing, the specimens were removed from the molds and stored under controlled conditions (moist or dry). The length of the specimens was measured at specific intervals over time at 7, 14, 28, 56, 91, 150 and 365 days using a comparator to assess any change. The change in length is calculated to determine the shrinkage of the mortar.

3. Results and Discussion

The results of fresh and hardened geopolymer concrete properties studied in the present study are mentioned in the proceeding sections along with the discussion.

3.1. Flowability

The flowability of geopolymer concrete was observed to be greatly influenced by the use of fibers, both steel and PVA. As the percentage of fibers in the geopolymer increased, the flowability decreased. Figures 1 and 2 show the plot of flowability of geopolymer concrete reinforced with steel fibers and PVA fibers, respectively. Geopolymer mix with only slag as a precursor (Mix HS1) displayed the least flowability when fibers were added to it. The hydrated lime from slag provides calcium in addition to silica and aluminum ions. These calcium ions act as a nucleus for precipitation and contribute to a rapid gel formation that stiffens the matrix. The geopolymer mix with both slag and silica fume as precursors (mixes HS2 and HS3) with both masonry sand and quartz as aggregates displayed increased flowabilities when compared to that with Mix HS1. Geopolymer mixes with fly ash included as one of the precursors (Mix HS4) with both steel and PVA

fibers displayed the highest flowability amongst the rest of the mixes. The spherical shape of fly ash particles contributed to better flow and reduced friction between adjacent particles, leading to a higher flowability. All mixes with PVA fibers in them displayed lesser flowability than their counterparts with steel fibers. The dispersion of PVA fibers into the matrix and its consecutive mixing led to fiber crimp occupying more volume and reducing flowability.

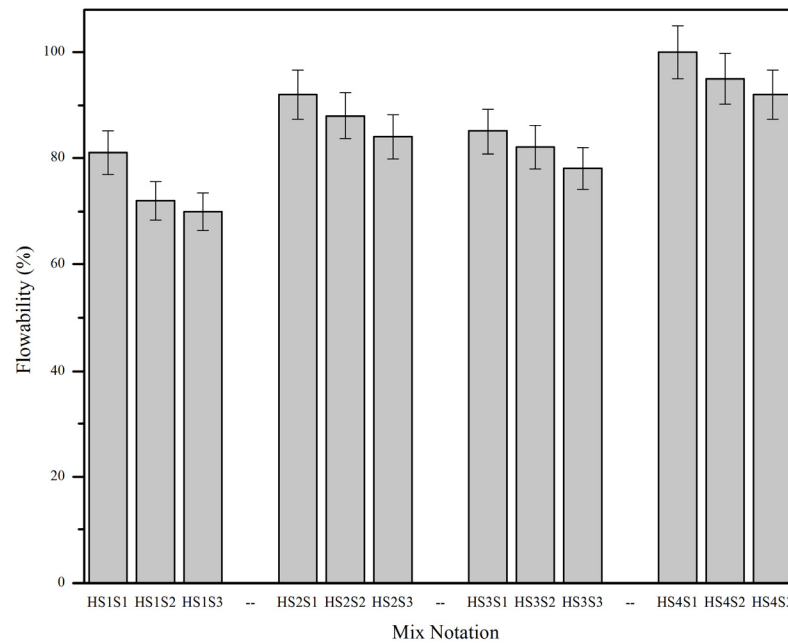


Figure 1. Flowability of geopolymer mixes with steel fibers.

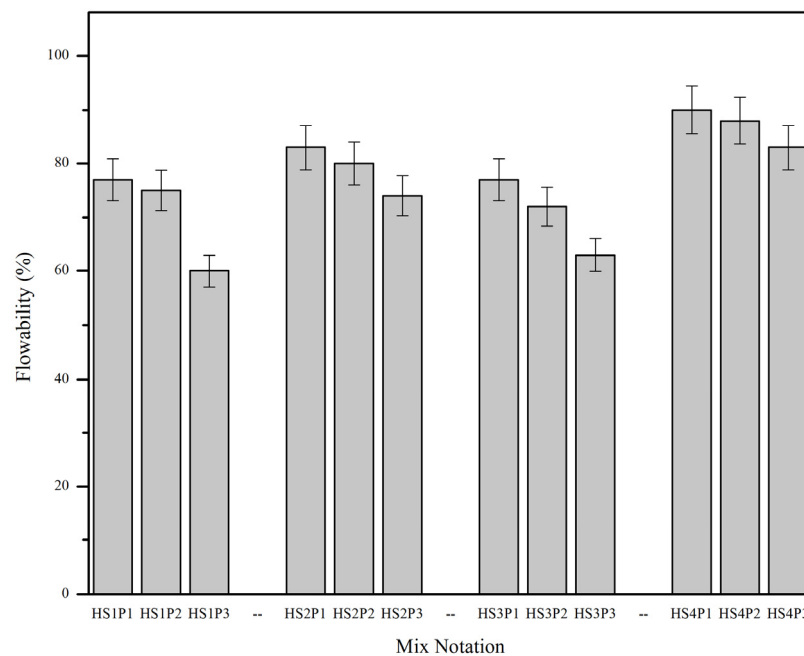


Figure 2. Flowability of geopolymer mixes with PVA fibers.

3.2. Compressive Strength

The compressive strength of hardened geopolymer specimens was measured after ambient curing for 7 days and 28 days. Geopolymer mixes with blast furnace slag as a precursor displayed the highest compressive strength, especially the mixes with 3% fiber volume. When the fibers were steel (HS1S3), a compressive strength of 107 MPa was achieved, and when the fiber was PVA (HS1P3), the same mix yielded a compressive strength of 82 MPa after 28 days of curing. An average increase of 25% in compressive strength was observed when the fibers increased from 1% to 3% in volume. The plot of compressive strength of mixes used in the study is presented in Figures 3 and 4. Steel fibers yielded higher strengths compared to their counterparts with PVA fibers due to their high modulus and tensile strength. Although silica fume is reported to have been used to improve the strength of geopolymer specimens due to plentiful available silica [48], the amorphous nature of silica needed high-temperature curing for geopolymerization reaction to proceed. As the study pertained to using ambient curing conditions, the geopolymer mixes with silica fume (Mixes HS2) did not yield strengths higher than blast furnace slag-based geopolymers. Quartz sand and quartz powder in the present study did not contribute to extra strength in the geopolymer mixes. Although quartz aggregate is known for its high hardness, inertness and continuous framework of silicon–oxygen tetrahedra, the particle size (2.36 mm) used in the present study rendered it weak against the denser geopolymer matrix, leading to microcrack development. Hence, the mixes denoted by HS3 yielded lesser compressive strengths compared to that of HS1 and HS2. Mixes denoted by HS4 that had fly ash, along with blast furnace slag and silica fume as precursors, yielded the least strength with 71 MPa at 28 days with 3% steel fiber volume. The glassy phases of alumina and silica in the fly ash remained largely unreacted owing to the ambient curing of the geopolymer samples.

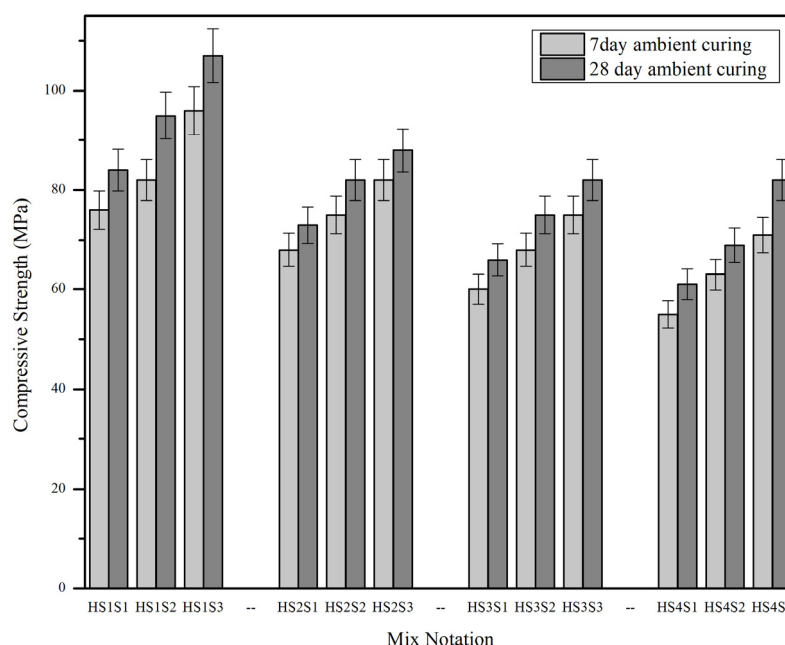


Figure 3. Compressive strength of geopolymer mixes with steel fibers.

3.3. Flexural Strength

The flexural strength of fiber-reinforced geopolymer specimens is plotted in Figures 5 and 6. The highest flexural strength of 16.4 MPa was observed in mix HS1S3 with blast furnace slag as precursor and steel fibers at 3% volume. Compared to steel fibers, PVA fibers yielded lesser flexural strength values again due to the difference in tensile strengths of both fibers. Steel fibers are more effective in bridging cracks and controlling crack propagation in geopolymer concrete. This crack-bridging capability is crucial for enhancing flexural

strength, as it allows the concrete to sustain greater loads before failure. The stiffness and rigidity of steel fibers allow them to bear and transfer loads more effectively within the geopolymer matrix. Most importantly, steel fibers tend to have a strong bond with the geopolymer matrix, ensuring efficient stress transfer and contributing to improved flexural performance. The trend in flexural strength results was similar to that of compressive strength, with 3% fiber giving the highest strength and the mixes with fly ash (HS4) yielding the least flexural strength among HS1, HS2, HS3 and HS4.

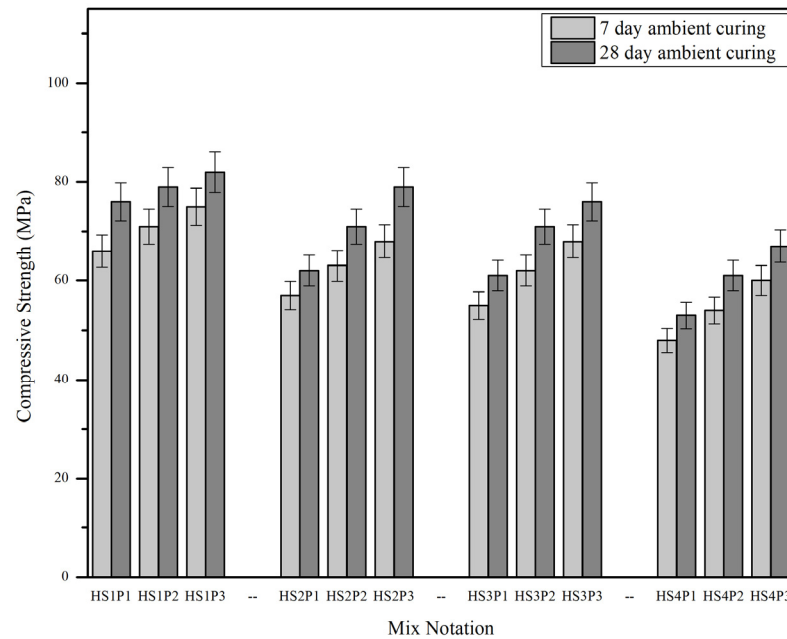


Figure 4. Compressive strength of geopolymer mixes with PVA fibers.

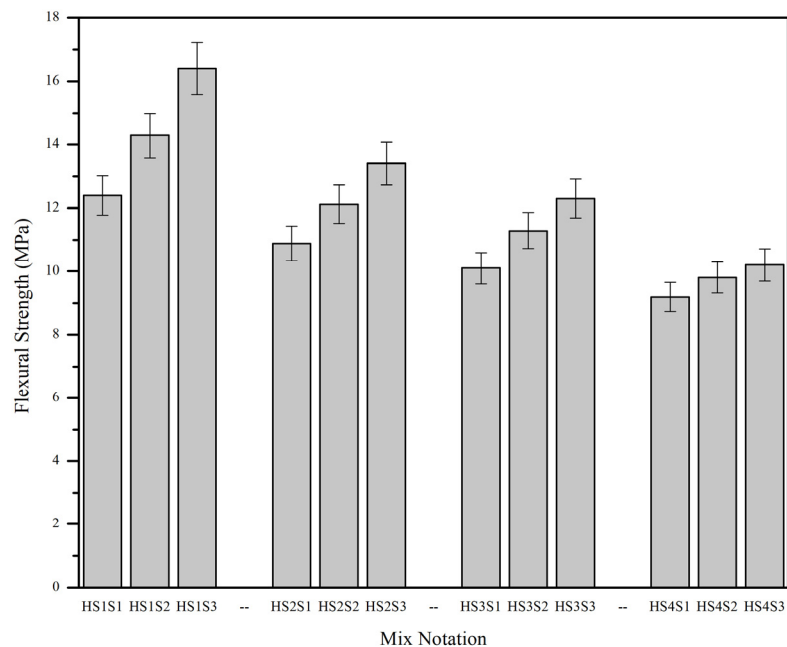


Figure 5. Flexural strength of geopolymer mixes with steel fibers.

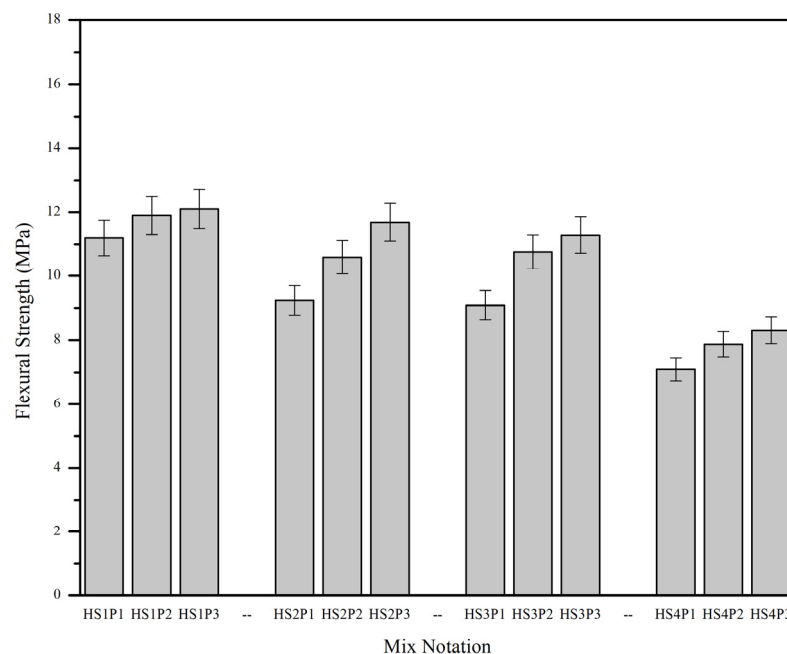


Figure 6. Flexural strength of geopolymer mixes with PVA fibers.

3.4. Drying Shrinkage

Drying shrinkage in Portland cement is primarily due to the loss of water from the hydrated cement. The shrinkage occurs as capillary water evaporates, leading to a reduction in the volume of the hydrated products, mainly calcium silicate hydrates. In geopolymers, drying shrinkage is influenced by the loss of physically bound water and the condensation of the geopolymer network. Geopolymers are typically aluminosilicate materials activated by an alkaline solution, forming a three-dimensional network with less free water than cement paste, hence less drying shrinkage compared to Portland. From the results of the present study, as shown in Figure 7, both steel and PVA fibers seemed to have had a profound effect on reducing the shrinkage of the geopolymer. The geopolymer mixes denoted by HS1 (blast furnace slag-based geopolymer) exhibited the highest shrinkage due to a more reactive and denser microstructure of slag, leading to more significant shrinkage as water evaporates. This was followed by mixes denoted by HS3 as the particle size of quartz aggregate led to a porous matrix and, thereby, more eventual shrinkage. The same mix with masonry sand (mixes denoted by HS2) exhibited less shrinkage due to silica fume, contributing to the formation of additional silicate structures in the geopolymer matrix, which helps to refine the pore structure and reduce the overall porosity and moisture loss during curing. The mixes with fly ash in them (denoted by HS4) displayed the least drying shrinkage as fly ash inclusion reduced the overall reactivity, which often results in lower shrinkage. The shrinkage of steel fiber-reinforced geopolymer was less compared to that of PVA fibers due to the high modulus values of steel fibers and its crack bridging ability.

3.5. Resistance to Acid Attacks

The geopolymer samples had been saturated in 5% sulphuric acid for 90 days after their 28 days of ambient curing. Geopolymer samples displayed good resistance against acid attack due to the absence of calcium hydroxide. The results of compressive strength post acid attack are presented in Figures 8 and 9. Mixes denoted by HS1 and HS4 with both steel and PVA fibers displayed the highest percentage loss in compressive strength. PVA fibers displayed better resistance against sulphuric acid compared to steel fibers. This is due to the corrosive nature of steel fibers under the attack of acid, whereas PVA fibers are more chemically stable and resistant to acid attacks. The decrease in strength is highest for mix HS4 and HS1 because the mixes denoted by HS4 had 20% fly ash in them, and

HS1 had only slag as a precursor. Fly ash geopolymer needs high-temperature curing, and as the study adopted ambient curing conditions, the unreacted fly ash particles led to a porous network, allowing the acid to leach into the matrix and deteriorate the geopolymer structure. Slag-based geopolymers, as they contain calcium ions, are susceptible to acid attack as they form calcium sulphate, which can lead to expansion and cracking. The geopolymer mixes denoted by HS2 and HS3, which had silica fume in them as precursors exhibited the best resistance against sulphuric acid attack due to better particle packing and the dense microstructure of silica fume, reducing the acid impregnation.

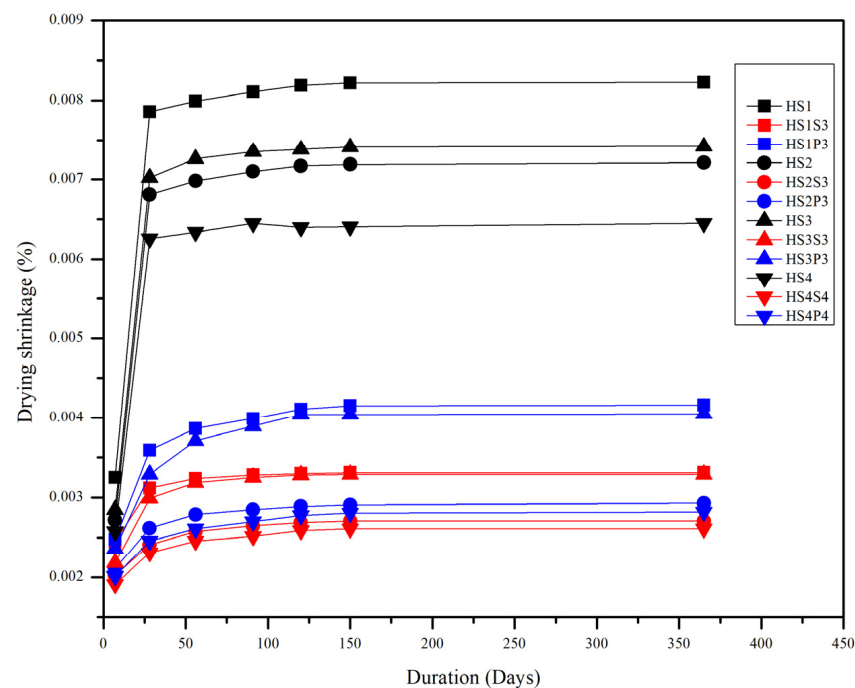


Figure 7. Drying shrinkage of the mixes used in the study.

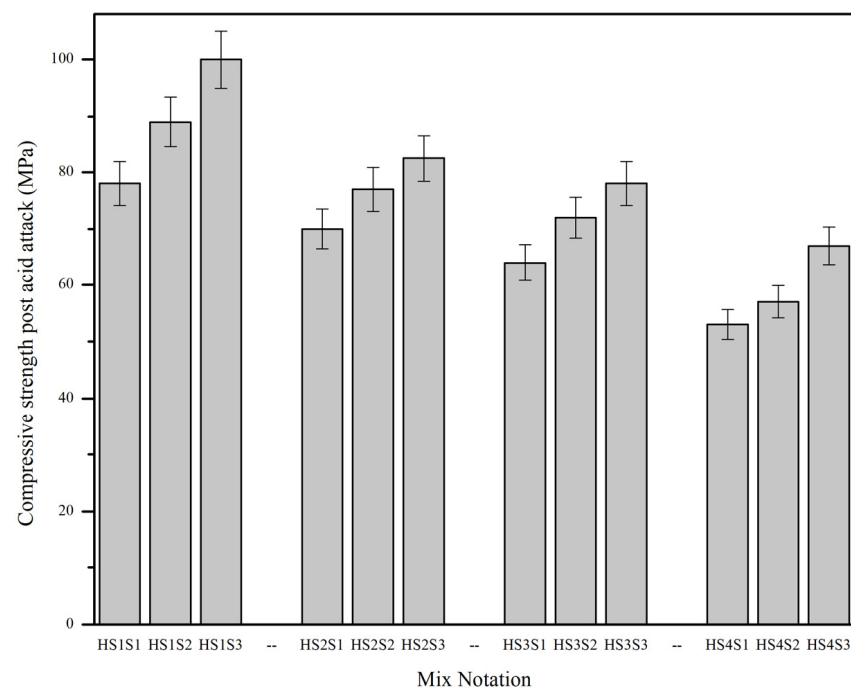


Figure 8. Compressive strength of geopolymer mixes with steel fibers post acid attack.

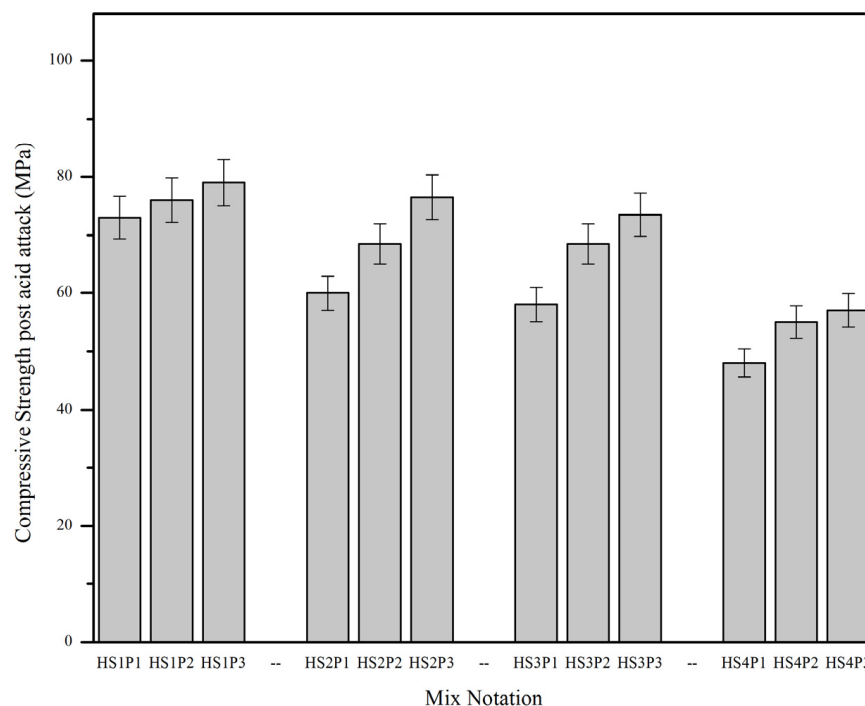


Figure 9. Compressive strength of geopolymer mixes with PVA fibers post acid attack.

3.6. Microstructural Analysis

The results of Scanning Electron Microscopy (SEM) on the samples with both steel fibers and PVA fibers are presented in this section. Mixes with 3% fibers by volume were used for the SEM analysis.

Figure 10a–d show the SEM micrographs of mixes with steel fibers in them. Figure 10a shows the steel fiber and its width (216 μm) embedded in the geopolymer matrix. Figure 10b depicts the formation of C-S-H needle-like structures from geopolymer mix HS1S3, indicating partial hydration in mixes with slag in them. Similar observations were made by Silva et al. [49] in their study of the fatigue behavior of steel fiber-reinforced geopolymer concrete. Figure 10c shows the steel fiber and geopolymer matrix along with the interfacial transition zone between them. Figure 10d is a zoomed-in SEM micrograph of the interfacial transition zone shown in Figure 10c, showing a superior bond between the fiber and the matrix.

Figure 11a–d show the SEM micrographs of mixes with PVA fibers in them. Figure 11a shows the width of PVA fiber (42 μm) used in the present study. Figure 11b depicts an interfacial transition zone between PVA fiber and geopolymer matrix where the fiber can be seen embedded in the matrix. Figure 11c,d show the flexibility of PVA fiber and crimping of fiber when mixed in the geopolymer matrix. This might be due to hydrolysis of the PVA in a strong base such as sodium hydroxide or due to the rapid mixing of the fibers along with geopolymer mortar. However, the acid attack resistance of PVA fiber-reinforced geopolymer outperformed steel fiber-reinforced geopolymer. A uniform microstructure of the geopolymer matrix with fewer pores contributes to its superior strength [50].

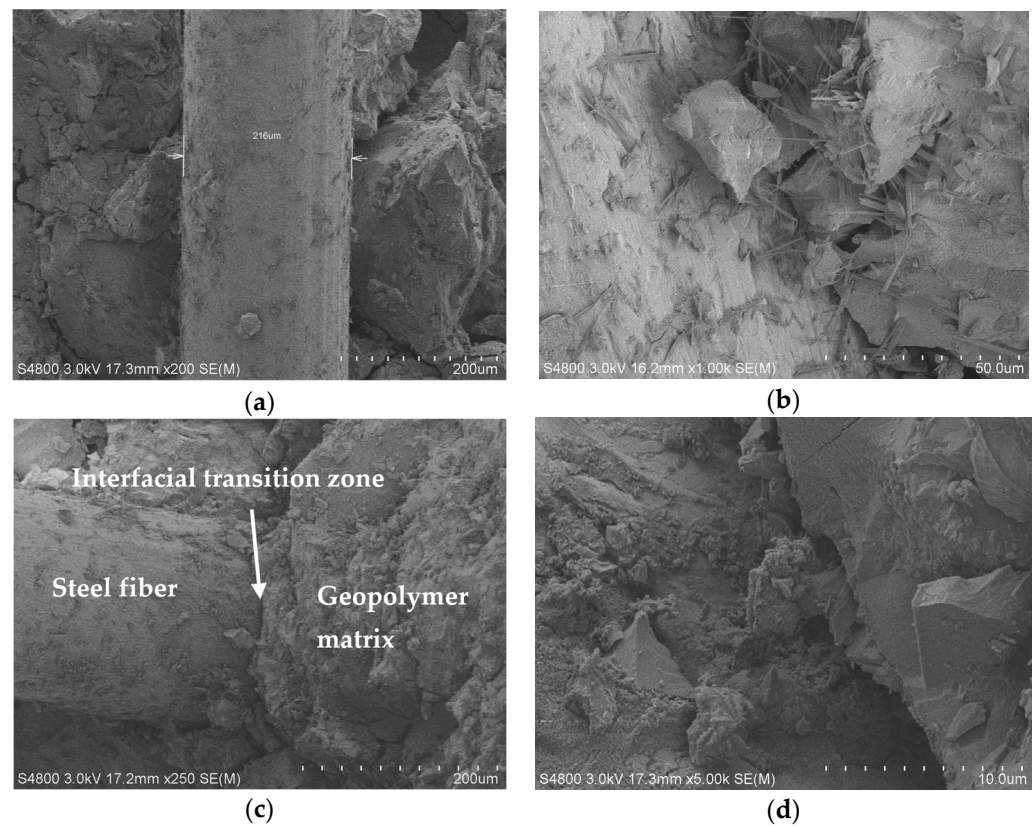


Figure 10. (a–d) SEM micrographs of geopolymer samples with steel fibers.

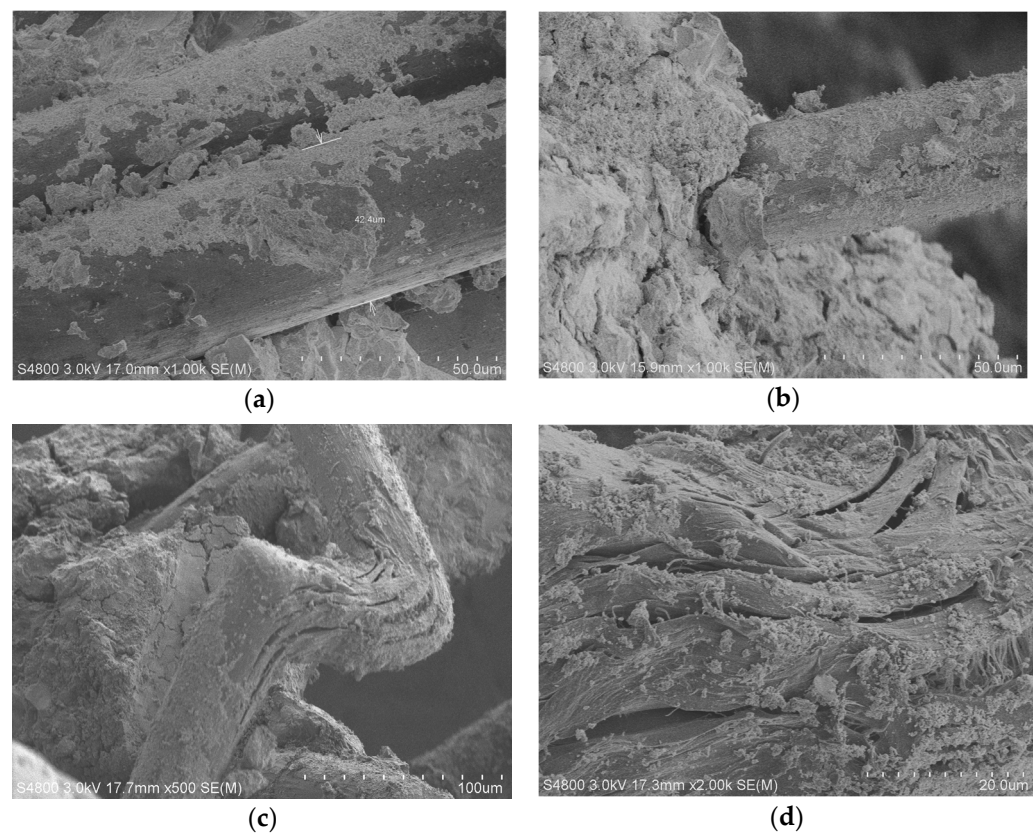


Figure 11. (a–d) SEM micrographs of geopolymer samples with PVA fibers.

4. Conclusions

The following conclusions on mechanical strength and durability performance have been drawn from the present study:

- (a) Blast furnace slag, as the only precursor (all mixes denoted by HS1) for geopolymer, yielded the highest strength and is the geopolymer when subjected to ambient curing.
- (b) The compressive strength of 3% steel fiber geopolymer with only slag as a precursor (HS1S3) yielded 107 MPa after 28 days of ambient curing, making it the optimum mix for achieving the highest mechanical performance. The same mix with PVA fiber (HS1P3) yielded a compressive strength of 82 MPa. The high strength of the steel fiber-reinforced geopolymer is due to the high tensile strength and modulus of steel fiber compared to PVA fiber.
- (c) Although PVA fibers did not yield compressive and flexural strengths greater than steel fibers, their performance against resisting sulphuric acid attack was observed to be superior to steel fibers. All the mixes with PVA fibers displayed a lesser drop (an average of 5.6%) in compressive strength compared to their counterparts with steel fibers which displayed a drop of 8.1% in compressive strength.
- (d) Geopolymer mixes with blast furnace slag as the precursor displayed the most shrinkage, followed by mixes with quartz sand. The presence of fibers mitigated most of the shrinkage, reducing it significantly. Steel fibers have been observed to display better resistance to shrinkage compared to PVA fibers. Also, the inclusion of silica fume has enhanced the shrinkage resistance of the geopolymer composites.
- (e) Blast furnace slag as a precursor and 3% steel fibers (HS1S3) based geopolymer displayed the highest flexural strength of 16.4 MPa. Steel fibers were crucial in mitigating the crack propagation and bridging crack widths, thereby enhancing the flexural strength.
- (f) Mixes that had slag displayed the least flowability, more so with fibers in them. The geopolymer mixes with PVA displayed the least flowability (HS1P3). Mixes with fly ash in them showed better flowability due to spherical particles of fly ash and reduced friction between particles.

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