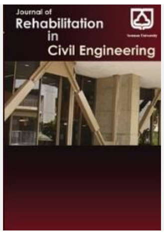

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Mechanical Performance of Slag-Based HPFRGC with Varying Silica Fume Replacement and Fiber Types

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ABSTRACT

As Portland cement production greatly affects the environment, more focus is being placed on using geopolymer concrete (GPC) as an alternative. This study explores the mechanical performance of high-performance fiber-reinforced geopolymer concrete (HPFRGC) using slag-based binders partially replaced with silica fume at levels of 0%, 5%, 10%, and 15%. The effects of incorporating steel and glass fibers at 0.5% and 1% volume fractions on compressive and splitting tensile strengths were also evaluated at 7 and 28 days. Results indicate that 5–10% silica fume replacement enhances compressive and tensile strength, with 10% being optimal. Excessive replacement (15%) reduced strength due to dilution of reactive content. Steel fibers were more effective than glass fibers, particularly at 1% content, yielding up to 12.7% and 38.6% improvements in compressive and tensile strengths, respectively. Moderate benefits were seen from using glass fibers, mainly in tensile performance. Failure pattern analysis showed that fiber-free specimens experienced brittle fractures, while fiber-reinforced mixes exhibited improved crack control and ductility. Overall, the combined use of 10% silica fume and 1% steel fiber offers the best enhancement in mechanical performance, suggesting an effective approach for developing sustainable, high-performance geopolymer concretes.

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1. Introduction

Portland cement is the main component in the common construction material known as concrete. As urbanization and industrialization speed up, we are using more concrete in our buildings. In many places, concrete is important for creating houses, dams, sidewalks, runways and roads and bridges [1–3]. Cement is a vital building material and therefore has a strong impact on the world's economy. Even so, heating cement to the necessary level produces a lot of greenhouse gases. Under high temperature in calcination, limestone decomposes into calcium oxide and releases carbon dioxide. The process contributes to about half of all emissions that come from cement production. [4].

Consequently, many studies have been focused on discovering options that decrease the use of cement while still providing the same engineering benefits. Geopolymers are a recently developed material that are formed by reacting aluminosilicate materials with alkaline solutions [5–7]. They are considered an alternative to cement for both partial and full replacement. According to Davidovits [8], geopolymer binders can be used to replace cement in many different types of construction projects. Geopolymers are valued for being eco-friendly and for using industrial by-products such as metakaolin [9],[10], fly ash [11],[12], ground granulated blast furnace slag (GGBFS) [13], [14],[15],[16] and others. High-volume use of ground granulated Blast furnace slag (GGBFS) has recently been studied in road pavement concrete, and it has shown positive effects on the strength and durability of the concrete. According to Mehdizadeh et al. [17], incorporating a high volume of GGBFS in road pavement concrete improves the sustainability of the concrete and increases its strength while lowering shrinkage.

Fibers added to geopolymer concrete (GPC) are now used to increase the overall strength and prevent cracks, solving the problems of low crack resistance and brittleness common in ordinary Portland cement [18], [19]. Carbon fibers, steel fibers and glass fibers have been proposed to enhance the mechanical properties of fiber reinforced geopolymer concrete (FRGPC). Every fiber type adds its own benefits to FRGPC. If 1% to 2% glass fiber is added to concrete, shrinkage cracks are reduced, flexural toughness increases, and the temperature resistance of the concrete improves. While glass fibers increase both split tensile and flexural strength in both conventional and recycled concrete, they do not significantly affect its compressive strength [20]. The strength and durability of concrete improve up to 1% with the addition of glass fiber, but increase quickly after that [21].

Still, although progress has been made, few researchers have looked at how fiber and binder changes affect geopolymer concrete together. Most research concentrates on single aspects of fibers or binders, but not on how their combination influences the strength of slag-based geopolymer concrete. This missing information in literature offers a valuable chance for researchers to study.

Previous studies clearly demonstrate that incorporating glass and steel fibers can significantly enhance the mechanical performance of geopolymer concrete (GPC), although such additions may also affect workability [22]. Building on these findings, the present study investigates the effects of glass and steel fibers on the mechanical properties—specifically compressive and splitting tensile strengths—of slag-based GPCs. Furthermore, this research examines the influence of partially replacing slag with silica fume as a supplementary binder. The primary objective is to evaluate the combined impact of fiber type and binder composition on the strength development of hybrid slag and silica fume-based geopolymer concrete.

Much is known about how individual aspects affect GPC, but the interaction between fiber type and partial silica fume replacement is understudied. This study is designed to examine the combined effect of these factors on the mechanical behavior of slag-based geopolymer concrete.

While concrete is frequently chosen, its strength is frequently weakened by corrosion in the steel reinforcement. For this reason, Glass Fiber Reinforced Polymer (GFRP) is now seen as a good alternative thanks to its strong anti-corrosion and strength properties. A recent example is the study done by Nouri et al. [23], which examines models that predict the actions of GFRP-reinforced concrete in severe environments. Additionally, Nouri, Ghanbari and Fakharian [24] also improved the performance of steel and GFRP reinforced beams by using optimization and ANOVA which revealed that the structural strength increased with a quadratic relationship to the reinforcement ratios. GFRP-reinforced concrete follows the potential of GPC which is sustainable and can be improved even further by adding GFRP reinforcement.

The present research advances the current state of knowledge by investigating the mechanical behavior of slag-based geopolymer concrete reinforced with two distinct types of fibers—glass and steel—at varying volume fractions. Moreover, it evaluates the influence of partially substituting slag with silica fume as a supplementary binder. The integrated assessment of fiber type and binder composition offers a novel framework for improving both the mechanical performance and environmental sustainability of GPC.

Using existing theories and research, we suggest the following research hypotheses:

1. Adding steel and glass fibers at 0.5% and 1% will improve the compressive and splitting tensile strengths of slag-based geopolymer concrete.
2. Partial replacement of slag with silica fume (up to 15%) will contribute to improved mechanical performance due to enhanced binder reactivity.

The primary objective of this study is to evaluate the mechanical performance of high-performance fiber-reinforced geopolymer concrete (HPFRGC) incorporating different binder compositions. Specifically, the research investigates the effects of replacing slag with silica fume at levels of 0%, 0.5%, 1%, and 1.5% in slag-based HPFRGC. Additionally, the influence of incorporating steel and glass fibers at volume fractions of 0.5% and 1% is assessed and compared to control mixes without fibers. The study also examines how different curing durations impact the mechanical behavior of HPFRGC with various fiber and binder combinations. Key mechanical properties, including compressive strength and splitting tensile strength, are measured to evaluate the overall performance of the developed mixes.

2. Materials and mix design

In Figure 1, the 20 GPC mixtures are organized and compared, and Table 1 gives the detailed mix proportions for every mixture. The mixes are prepared using slag, silica fume, a liquid alkaline activator, silica sand aggregates and steel and glass fibers. The codes for mixes with fibers are as follows: MS indicates the amount of silica fume used instead of slag, SF is for steel fiber and GL is for glass fiber. The last digits on SF or GL mean the percentage of steel fiber or glass fiber (so SF1 is 1% steel fiber and GL0.5 is 0.5% glass fiber).

Figure 1 also shows the scenarios that were investigated during this experiment. Three main comparison frameworks were created. First, the performance of geopolymer concrete with slag replaced by silica fume at 5%, 10% and 15% was examined and compared to the fully slag-based mix (called MS0-CTRL). The study also investigated what happens when steel and glass fibers are added at 0.5% and 1% volume fractions. The effects of fiber reinforcement were evaluated by comparing these mixes to a plain reference mix in each group. Group 1 used only slag in the geopolymer concrete, while groups 2, 3 and 4 had 5%, 10% and 15% silica fume replacement. The third step compared curing time, measuring the strength after 7 days and again after 28 days to see how it changed.

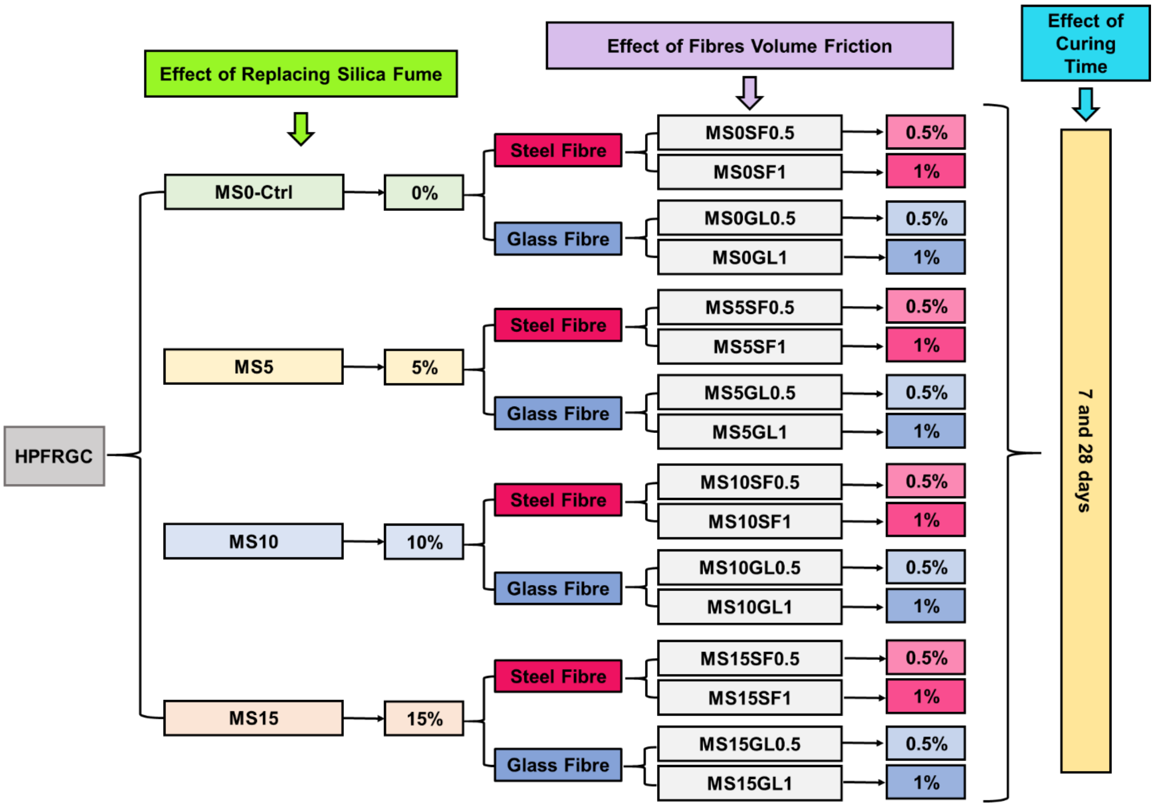


Fig. 1. Categories of mix designs and comparison scenarios used in this study.

Table 1. Mix proportions geopolymer concretes.

No	Mix ID	Slag	Silica Fume	Sand		Fiber		Na_2SiO_3	NaOH	SS/SH	NaOH Molarity
		(Kg/m³)	(Kg/m³)	T181 Quartz (Kg/m³)	T141 Quartz (Kg/m³)	(Kg/m³)	V (%)	(Kg/m³)	(Kg/m³)		
1	MS0-Ctrl	700	0	640	640	0	0	250	100	2.5	10
2	MS5	665	35	640	640	0	0	250	100	2.5	10
3	MS10	630	70	640	640	0	0	250	100	2.5	10
4	MS15	595	105	640	640	0	0	250	100	2.5	10
5	MS0SF0.5	700	0	640	640	39.25	0.5	250	100	2.5	10
6	MS5SF0.5	665	35	640	640	39.25	0.5	250	100	2.5	10
7	MS10SF0.5	630	70	640	640	39.25	0.5	250	100	2.5	10
8	MS15SF0.5	595	105	640	640	39.25	0.5	250	100	2.5	10
9	MS0SF1	700	0	640	640	78.50	1.0	250	100	2.5	10
10	MS5SF1	665	35	640	640	78.50	1.0	250	100	2.5	10
11	MS10SF1	630	70	640	640	78.50	1.0	250	100	2.5	10
12	MS15SF1	595	105	640	640	78.50	1.0	250	100	2.5	10
13	MS0GL0.5	700	0	640	640	3.25	0.5	250	100	2.5	10
14	MS5GL0.5	665	35	640	640	3.25	0.5	250	100	2.5	10
15	MS10GL0.5	630	70	640	640	3.25	0.5	250	100	2.5	10
16	MS15GL0.5	595	105	640	640	3.25	0.5	250	100	2.5	10
17	MS0GL1	700	0	640	640	6.50	1.0	250	100	2.5	10
18	MS5GL1	665	35	640	640	6.50	1.0	250	100	2.5	10
19	MS10GL1	630	70	640	640	6.50	1.0	250	100	2.5	10
20	MS15GL1	595	105	640	640	6.50	1.0	250	100	2.5	10

Figure 2 presents a graphical representation of the chemical composition of the binders used in this study. The chemical characteristics of both silica fume and slag were obtained from the data provided by their respective suppliers and are detailed in Tables 2 and 3, respectively.

Table 2. Chemical properties of used silica fume.

Chemical Properties	CL	SO_3	P_2O_5	K_2O	Na_2O	H_2O	SiC	C	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO
Percentage (%)	0.04	0.1	0.16	1.01	0.31	0.08	0.5	0.3	96.4	0.87	1.32	0.49	0.97

Table 3. Chemical properties of used Ferrous slag.

Chemical Properties	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2
Percentage (%)	37.4	27.6	7.4	20.5	2.8	0.5	0.8	3

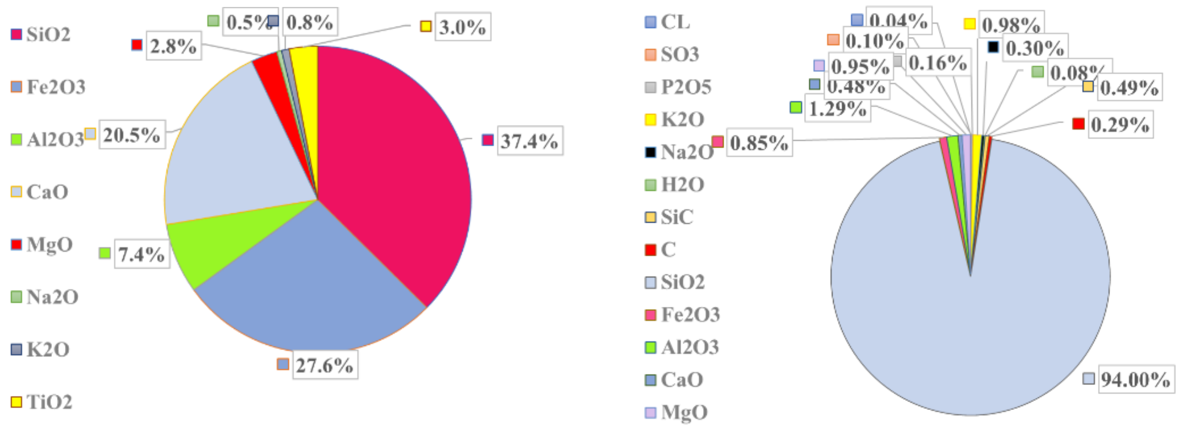


Fig. 2. Chemical composition of a) slag and b) silica fume.

The alkaline activator was prepared by combining sodium hydroxide (NaOH) solution and sodium silicate (Na_2SiO_3) solution at a ratio of $\frac{Na_2SiO_3}{NaOH} = 2.5$. Two different size ranges of quartz sand were used: 0.09–0.35 mm for T181 and 0.18–0.71 mm for T141. The physical properties of the quartz sand are presented in Table 4. The masses of T181 and T141 aggregates were both considered to be 640 kg per $1m^3$ of geopolymer concrete (GPC).

Two types of fibers, glass and steel were incorporated into the GPC as shown in Figure 3. The physical properties of the glass and steel fibers are presented in Tables 5 and 6, respectively.

Table 4. Physical characteristics of aggregates.

Properties	T181 Quartz sand	T141 Quartz sand
Specific gravity	2.6	2.67
Water absorption	0.93	1.06
Aggregate size	0.09-0.35 mm	0.18-0.71 mm
Fineness Modulus	0.7	2.4

Table 5. Steel fiber's physical properties.

Properties	Value
Length (mm)	25
Density (Kg/m^3)	7850
Diameter (mm)	8
Tensile Strength (MPa)	800-1200
Bending Strength (MPa)	180-210
Section Type	Circular
Type	Straight

Table 6. Glass fiber's physical properties.

Properties	Value
Length (mm)	6
Density (Kg/m^3)	2680
Diameter (mm)	0.014
Young's Modulus (MPa)	1700
Chemical resistance	high
Thermal degradation (%)	0.55
Softening point (˚C)	860

Steel fibers Glass fibers

Fig. 3. Fibers used in the study.

3. Mixing and curing procedure

Concrete mixes were created using the selected materials based on general mix design guidelines, as indicated in previous studies [4], [14]. The mixes were cast under laboratory conditions with a temperature of 23 ± 2°C. The alkaline solution comprising NaOH and Na_2SiO_3 were mixed 24 hours before. The production of geopolymer concrete involves homogeneous mixing of constituent materials. Uniform mixing of concrete in gradients produce concrete with better strength properties. In the first stage, two different types of silica fine aggregates were mixed for about 1 minute, and then binder solids (slag or slag + silica fume) were added. For mix designs consisting of fibers, steel or glass fibers were added and mixed for about 1.5 minutes, then the alkaline solution was gradually added and mixed for about 1.5 minutes. The mixing operation was continued up to 1.5 minutes after complete addition of alkaline solution. This has given a more workable concrete with better strength properties. Increasing the mixing time after addition of solution will increase the properties of concrete like workability and strengths which are much superior [25].

The superplasticizer was put into the same container as the alkali activator and then added to the concrete mix. High-strength concrete was produced using high-range water-reducing superplasticizers. The use of the polycarboxylic ether superplasticizer allowed for a 15% drop in water which lowered the water-to-binder ratio and improved the strength of the concrete. This step also helped create a more balanced and workable mix, something especially needed in this research given the large amount of fibers used. All mixes were prepared with a superplasticizer at a constant rate of 2.5% by binder weight.

The slump test was in line with ASTM C143-15 [26] and the average slump was measured as 70 mm. The prepared mix was poured into molds, and air bubbles were removed using a vibrating table. Since the mix using only fine aggregates is highly workable within a slump range of 50 to 150 mm and because vibration plays a big role in compacting such mixes, the best compaction method is using a vibrating table, according to ASTM C31 [27]. Vibration makes the aggregates slide more easily, so they settle nearer to one another, and air bubbles are able to rise easily. After 24 hours was up, the samples were removed from their molds and cured by placing them in water at 23°C in line with ASTM C31 [27].

The samples were water-cured for 7 and 28 days in a laboratory with a temperature of 23 °C before testing. In this case, heat curing was not used because the aim was to test the material as it would be used in real situations, where raising the temperature is difficult such as when repairing structures.

In Figure 4, there is a schematic that outlines the selection of materials, the sequence of mixing, casting the concrete and the curing steps needed to make high-performance fiber-reinforced geopolymer concrete. Table 7 provides a summary of the total number of samples cast for all types of tests for geopolymer concrete, along with the relevant standards.

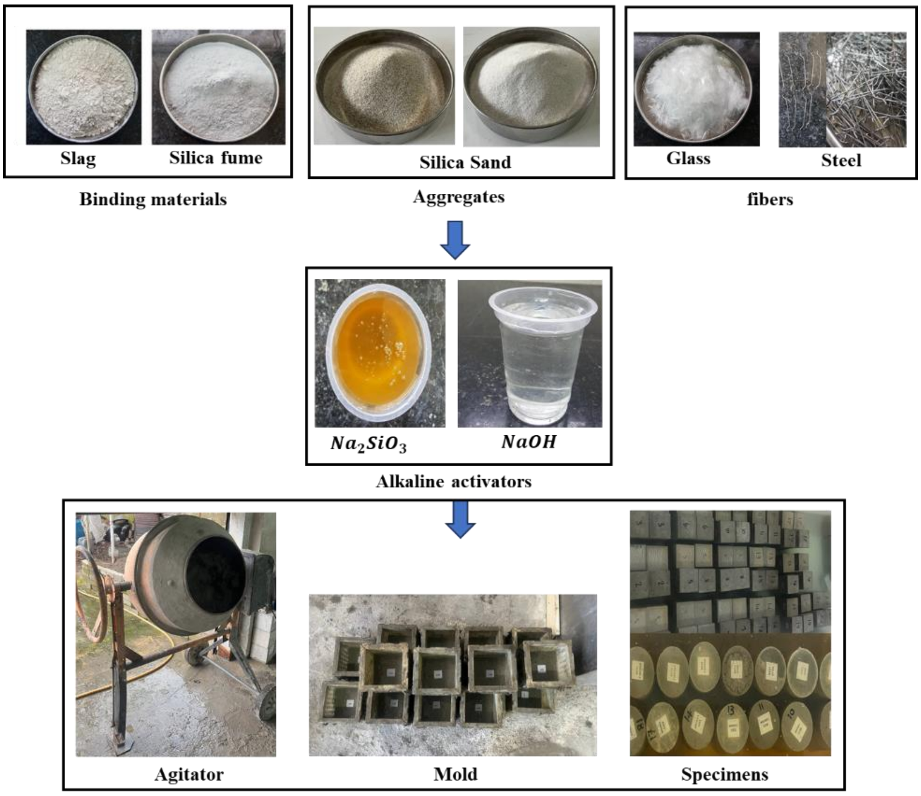


Fig. 4. Schematic diagram illustrating the process of manufacturing of HPFRGC.

Table 7. Geopolymer concrete testing specifications.

Test Type	Standard	Shape	Age (Days)	Condition	No. of Samples
Compressive Strength	BS EN12390-3 [28]	Cube 50×50 mm	7, 28	conventional environment	200
Split Tensile Strength	C496/C496M [29]	Cylinder 100×200 mm	7, 28		200

4. Description of tests

The tests performed in this research were related to evaluating the mechanical characteristics of high-performance fibers reinforced geopolymer concrete. The outcomes of all the various tests are detailed in the subsequent sections. The mechanical tests of GPC consist of compressive strength test (CTS) and splitting tensile strength (STS) according to figure 5. The compressive strength of GPC cube specimens was tested using a 3000 kN capacity compression machine as per BS EN 12390-3 [28], with 5 cubic molds (50×50×50 mm) per mix tested at 7, and 28 days. The split tensile strength test followed ASTM C496/C496M-17 [29], using the same machine, with three-cylinder molds (100×200 mm) per mix using the formula $T = 2P/\pi LD$.

The compressive strength of the HPFRGC specimens was evaluated using 50 mm cube molds in accordance with BS EN 12390-3 [28] standards. The small size of the specimens was dictated by the finer mixes which did not include coarse aggregates and thus more closely matched the composition of mortar. This approach matches where these materials are used, as thin layers in repairs or surface-strengthening materials, where the smaller samples can be analyzed with greater detail. Furthermore, the use of 50 mm cubes makes it easier to compare the performance of different mixes by providing the same level of compaction and curing.

(a) (b)

Fig. 5. Testing machine for a) Compressive b) Tensile strength test of concrete cubes and cylinders.

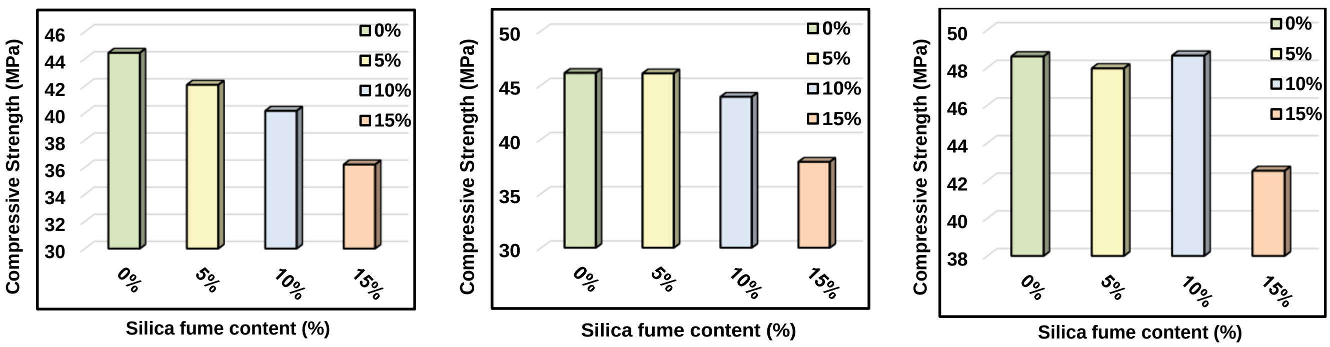
5. Results and discussion

5.1. Effect of silica fume content on mechanical properties

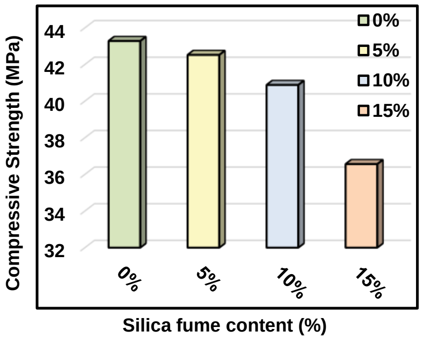
5.1.1. Effect of silica fume content on compressive strength

The influence of varying silica fume content (0%, 5%, 10%, and 15%) as a partial replacement for slag on the compressive strength of fiber-free geopolymer concrete was evaluated at both 7 and 28 days of curing. The compressive strength results of HPFRGC mixes after 7 and 28 days of curing are presented in Figure 6 and Figure 7, respectively. Each figure consists of five subplots representing different fiber groups: fiber-free, 0.5% steel fiber, 1% steel fiber, 0.5% glass fiber, and 1% glass fiber, allowing for a detailed comparison of the effects of fiber type and content.

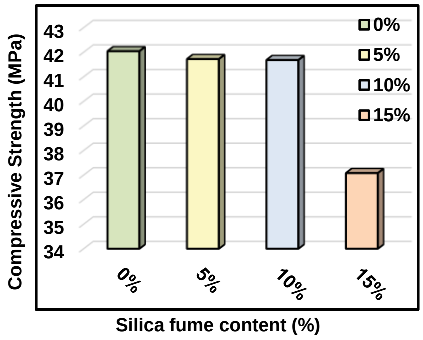
At early age (7 days), the compressive strength of the control mix (0% silica fume) reached 44.44 MPa. With the introduction of silica fume, a general decreasing trend was observed. The mix containing 5% silica fume exhibited a slight reduction to 42.08 MPa (–5.3%), while further increases to 10% and 15% replacements resulted in more pronounced strength reductions to 40.16 MPa (–9.6%) and 36.20 MPa (–18.5%), respectively.



a) fiber free b) 0.5% steel fiber c) 1% steel fiber



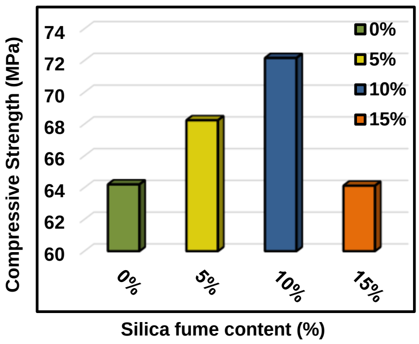
d) 0.5% glass fiber



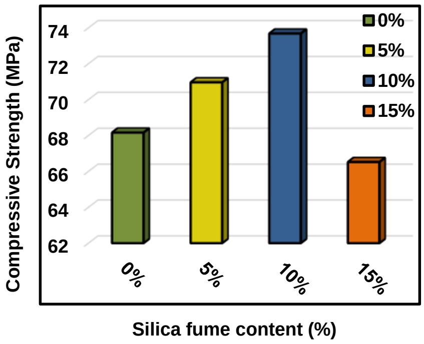
e) 1% glass fiber

Fig. 6. The compressive strength results of HPFRGC mixes after 7 days of curing.

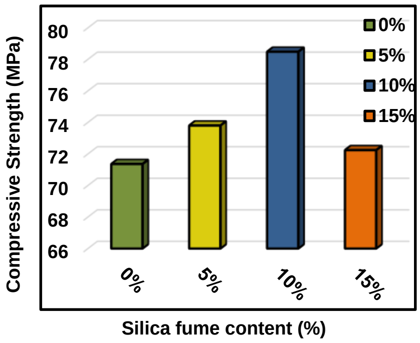
The reason for reduced strength in the early stages is that geopolymerization happens more slowly when there is more silica fume in the mix. Because silica fume is very active in the final stages, it can slow the first development of strength in the concrete since its fine particles and high silica content absorb the alkalis and delay the initial gel process. The results obtained in this study are consistent with the findings reported by Mohamed et al. [30], where the inclusion of silica fume in alkali-activated slag-based binders led to a reduction in compressive strength due to delayed geopolymerization reactions.



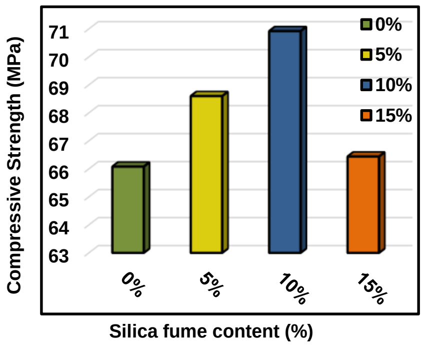
a) fiber free



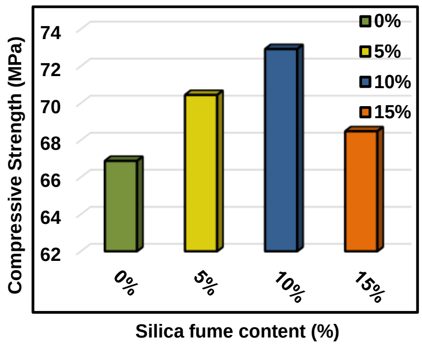
b) 0.5% steel fiber



c) 1% steel fiber



d) 0.5% glass fiber



e) 1% glass fiber

Fig. 7. The compressive strength results of HPFRGC mixes after 28 days of curing.

Unlike the early-age results, the 28-day strength data revealed a positive effect of silica fume on long-term strength development, especially at 5% and 10% replacement levels. The compressive strength increased from 64.20 MPa in the control mix to 68.24 MPa (+6.3%) and 72.16 MPa (+12.4%) for 5% and 10% silica fume content, respectively. The highest strength was observed at 10% replacement, suggesting an optimal balance between reactivity and microstructural enhancement.

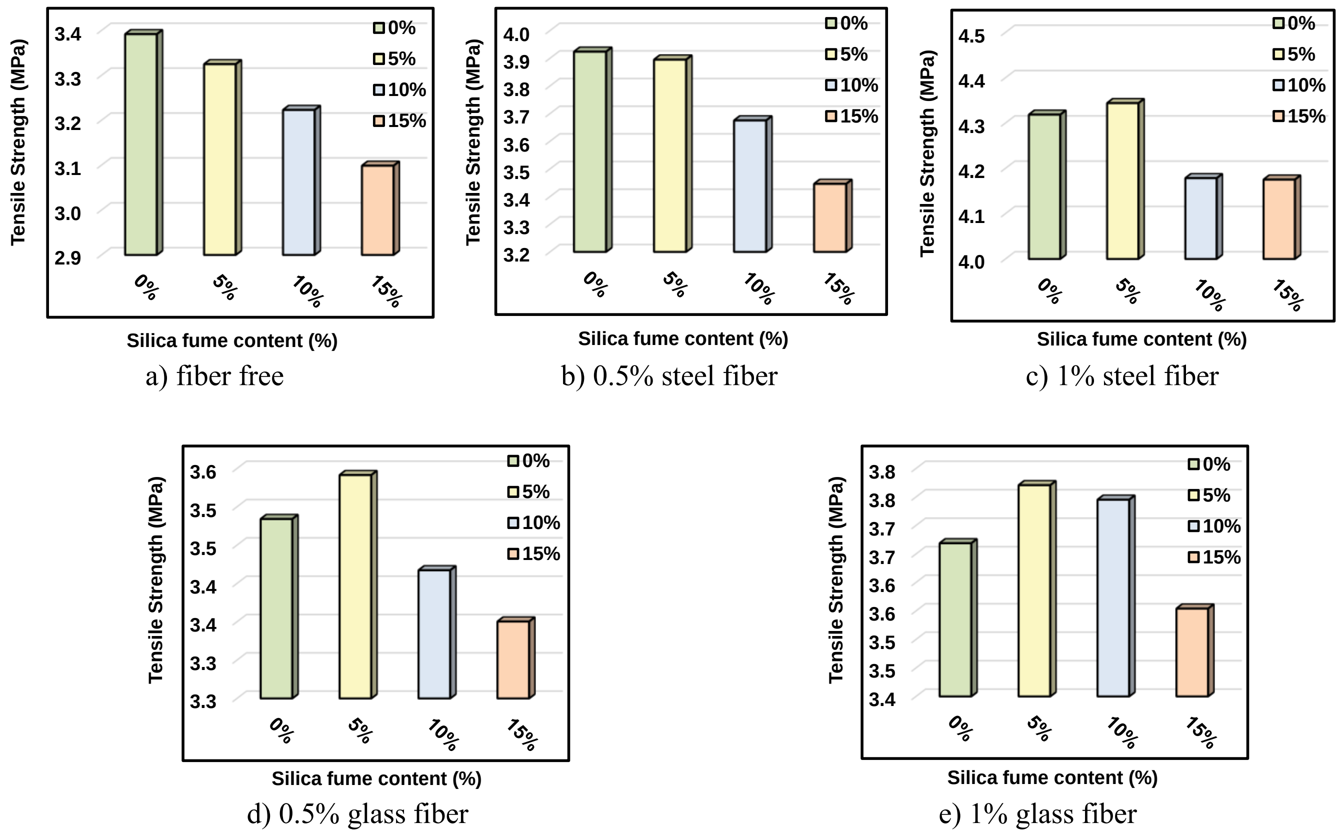
However, increasing the silica fume to 15% slightly reduced strength to 64.12 MPa, comparable to the control mix (–0.1%). These results indicate that moderate amounts of silica fume contribute positively to compressive strength at later ages by promoting denser microstructure, increased geopolymer gel formation, and enhanced packing density due to its ultrafine particle size. However, excessive replacement (15%) may dilute the reactive aluminosilicate content and hinder overall binder efficiency.

5.1.2. Effect of silica fume content on tensile strength

The splitting tensile strength (STS) results for all HPFRGC mixes at 7 and 28 days are illustrated in Figures 8 and 9, respectively. Each figure includes five groups corresponding to: fiber-free, 0.5% steel fiber, 1% steel fiber, 0.5% glass fiber, and 1% glass fiber.

At 7 days, the fiber-free mixes showed a slight decrease in tensile strength with increasing silica fume content. Compared to the control mix (MS0-Ctrl) with 3.39 MPa, mixes with 5%, 10%, and 15% silica fume replacements showed reductions of approximately 1.97%, 4.98%, and 8.64%, respectively. This trend suggests that early-age strength development may be hindered by excessive silica fume due to slower geopolymerization or reduced calcium content affecting the matrix strength.

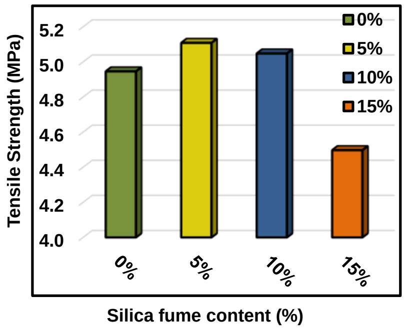
At 28 days, however, the tensile strength showed improvement with up to 10% silica fume replacement. MS10 achieved a tensile strength of 5.05 MPa, which was 2.06% higher than the control mix, while MS5 showed a 3.28% increase. The mix with 15% replacement (MS15) again displayed a noticeable drop (-9.08%) in tensile strength, suggesting that the optimum silica fume content lies around 5–10% for fiber-free mixes.



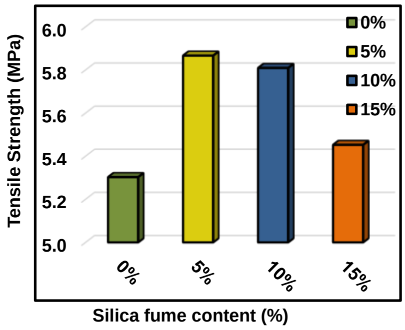
a) fiber free b) 0.5% steel fiber c) 1% steel fiber

d) 0.5% glass fiber e) 1% glass fiber

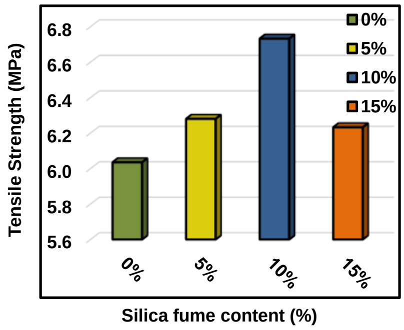
Fig. 8. The tensile strength results of HPFRGC mixes after 7 days of curing.



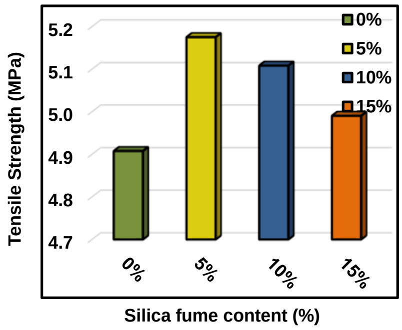
a) fiber free



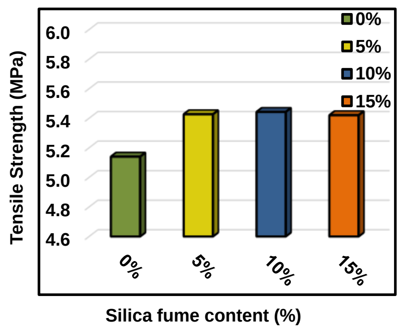
b) 0.5% steel fiber



c) 1% steel fiber



d) 0.5% glass fiber



e) 1% glass fiber

Fig. 9. The tensile strength results of HPFRGC mixes after 28 days of curing.

The incorporation of steel and glass fibers significantly enhanced tensile strength at both curing ages. The highest improvement was observed in mixes containing 1% steel fiber, with MS10SF1 reaching 6.73 MPa (a 36.12% increase) at 28 days and 4.18 MPa (a 23.19% increase) at 7 days. Glass fiber helped increase the tensile strength, but not as much as steel fiber did. The MS10GL1 showed an improvement of 10.05% at 28 days and 10.42% at 7 days.

These results indicate that moderate silica fume replacement (5–10%), combined with fiber reinforcement—particularly 1% steel fiber—results in enhanced tensile strength performance in HPFRGC. The synergistic effect between fiber bridging and the refined matrix due to silica fume may explain this behavior. The results obtained in this study are in agreement with the findings of Memon et al. [31], who reported that the incorporation of silica fume improves the tensile strength of geopolymer concrete due to enhanced matrix densification and fiber–matrix interaction.

5.2. Effect of fiber type and content on mechanical properties

5.2.1. Effect of fiber type and content on compressive strength

The compressive strength results of the HPFRGC mixes with varying silica fume content (0%, 5%, 10%, and 15%) are presented in Figure 10 and 11 for 7-day and 28-day curing periods, respectively. In each subfigure, the legend "0%" refers to fiber-free mixes, "0.5%-SF" and "1%-SF" denote 0.5% and 1% steel fiber content, and "0.5%-GF" and "1%-GF" represent 0.5% and 1% glass fiber content, respectively The addition of steel fibers significantly improved the compressive strength of all mixes, particularly at higher fiber content. Across all silica fume replacement levels, mixes with 1% steel fiber consistently demonstrated the highest compressive strength. For instance, at 10% silica fume, the 1% steel fiber mix (MS10SF1) achieved a 21.1% increase in 7-day strength and an 8.8% increase at 28 days compared to the fiber-free mix. Similarly, at 15% silica fume, the addition of 1% steel fiber led to strength gains of 17.5% and 12.7% at 7 and 28 days, respectively. This enhancement is attributed to the confinement effect of steel fibers, which delays crack propagation and improves stress distribution within the matrix, especially in denser mixes resulting from silica fume incorporation.

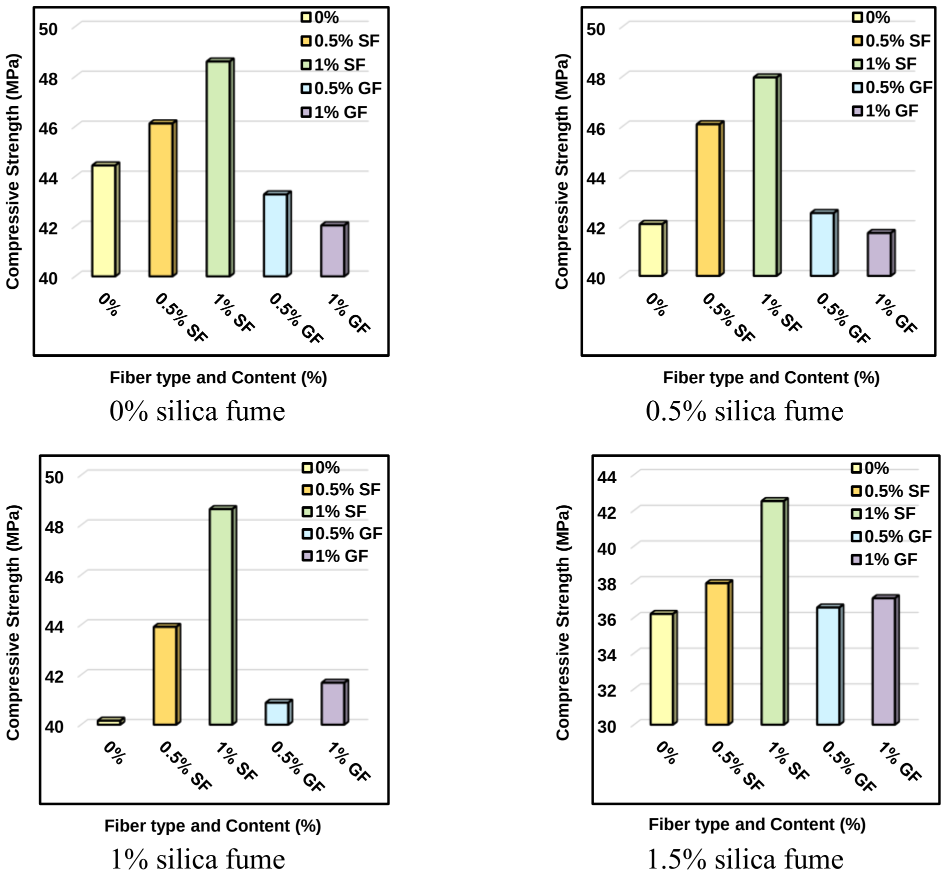


Fig. 10. The compressive strength results of HPFRGC mixes after 7 days of curing.

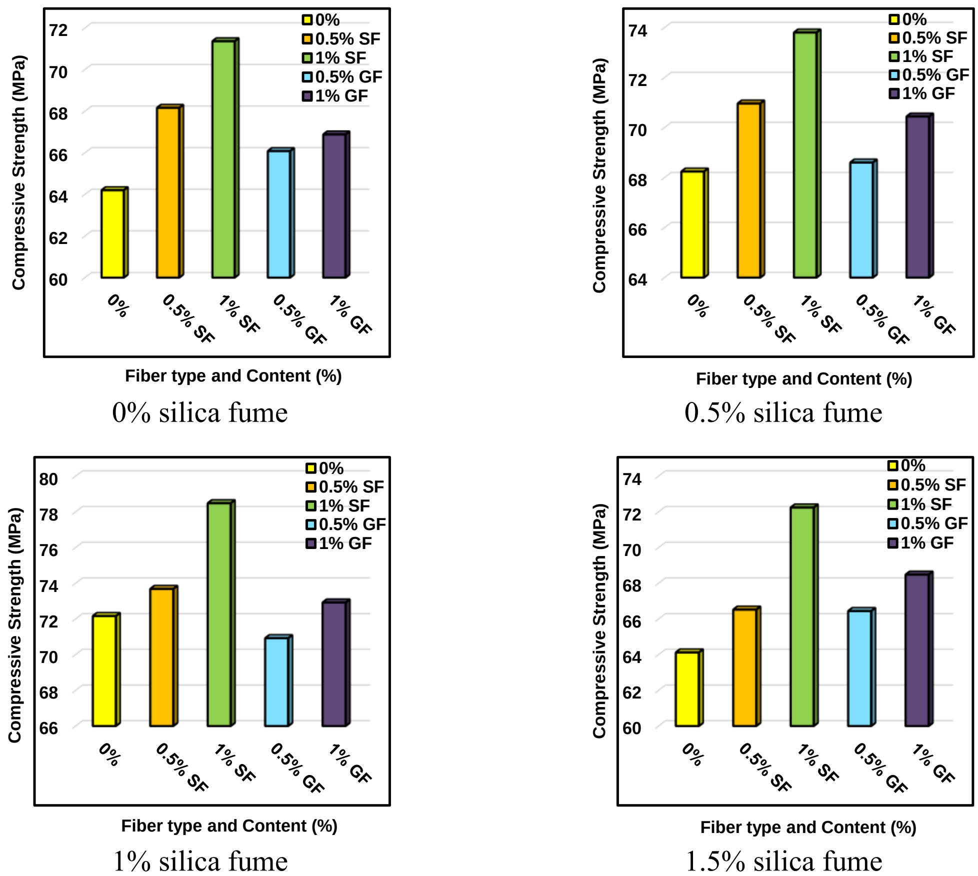


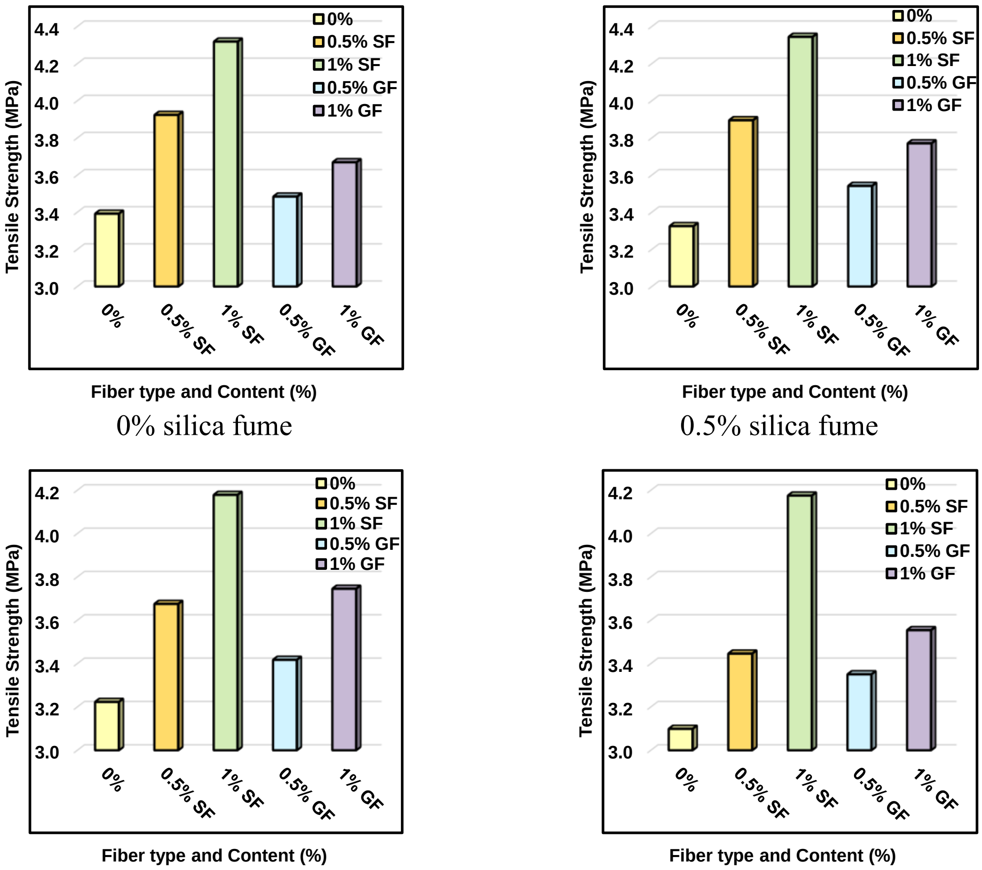
Fig. 11. The compressive strength results of HPFRGC mixes after 28 days of curing.

Conversely, the inclusion of glass fibers resulted in a less significant and more variable influence on the measured properties. At 0.5% glass fiber content, the improvement in compressive strength was marginal or even negative in some cases. Increasing the glass fiber content to 1% showed slight gains, particularly at 28 days—for example, MS15GL1 showed a 6.8% improvement over the fiber-free mix. However, the overall contribution of glass fibers remained lower than that of steel fibers, likely due to their lower modulus of elasticity and weaker bond with the matrix under compressive loads. In summary, 1% steel fiber content provided the most notable improvements in compressive strength across all silica fume levels and curing ages, making it the optimal fiber type and dosage for enhancing the compressive performance of HPGFRC. Glass fibers, although beneficial to a limited extent, were more effective in boosting tensile rather than compressive behavior.

5.2.2. Effect of fiber type and content on tensile strength

The tensile strength results of the HPFRGC mixes with varying silica fume content (0%, 5%, 10%, and 15%) are presented in Figures 12 and 13 for 7-day and 28-day curing periods, respectively. In each subfigure, the legend "0%" refers to fiber-free mixes, "0.5%-SF" and "1%-SF" denote 0.5% and 1% steel fiber content, and "0.5%-GF" and "1%-GF" represent 0.5% and 1% glass fiber content, respectively.

The incorporation of steel and glass fibers had a significant impact on the tensile performance of the mixes. In general, the addition of steel fibers showed a more pronounced improvement compared to glass fibers, especially at 1% dosage. For instance, at 0% silica fume content, 1% steel fiber increased the 7-day and 28-day tensile strength by approximately 27% and 22%, respectively, over the fiber-free control mix. This trend continued across all silica fume levels, with the MS15SF1 mix (15% silica fume, 1% steel fiber) achieving the highest tensile strength at 28 days, improving by over 38.6% compared to the corresponding fiber-free mix. This enhancement is primarily attributed to the excellent crack-bridging ability and stiffness of steel fibers, which become especially effective in the denser matrix formed by silica fume.



0% silica fume

0.5% silica fume

1% silica fume

1.5% silica fume

Fig. 12. The tensile strength results of HPFRGC mixes after 7 days of curing.

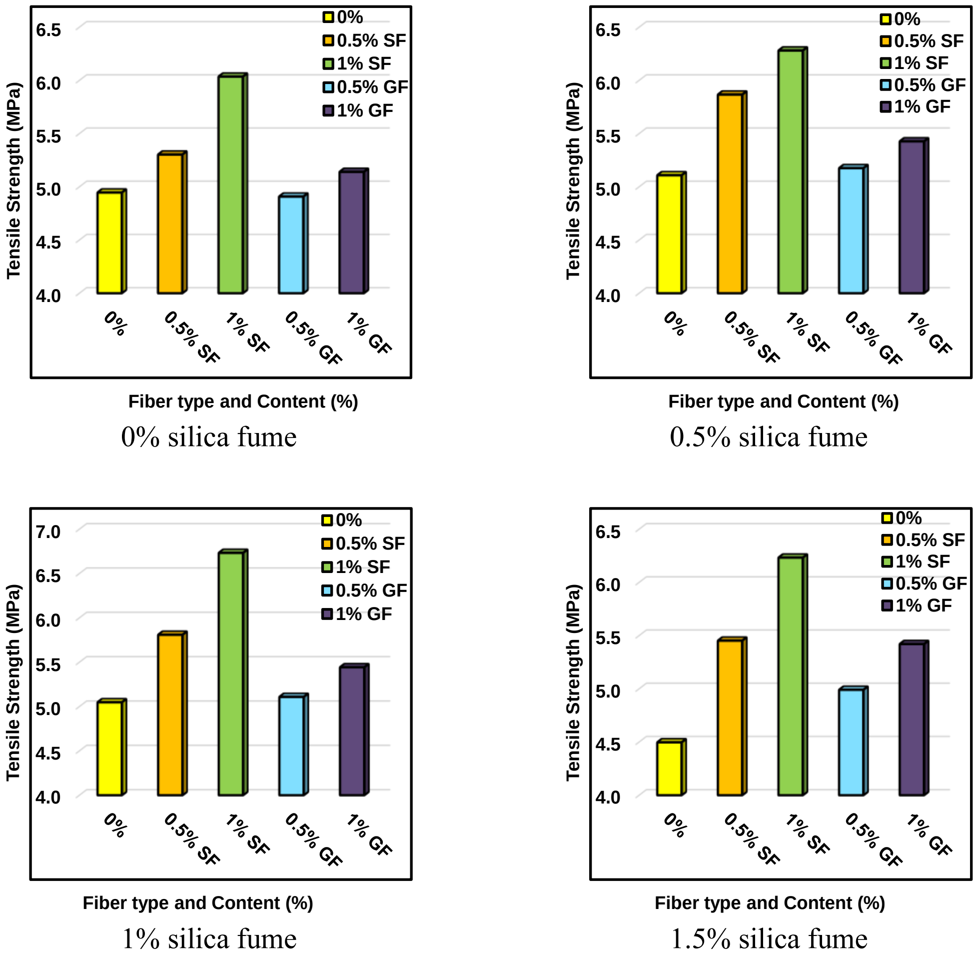


Fig. 13. The tensile strength results of HPFRGC mixes after 28 days of curing.

Although glass fibers improved the strength, other additives had a greater effect. At 1% content, glass fibers generally increased tensile strength, though the gain was lower than that provided by steel fibers. For example, in the mix with 15% silica fume, 1% glass fiber improved 28-day strength by around 20.5% compared to the fiber-free mix. The improvements from 0.5% glass fiber were generally modest, with some early-age gains and minimal or negative changes at 28 days. The reduced effectiveness of glass fibers can be linked to their lower stiffness and relatively weaker bond with the geopolymer matrix.

Overall, the data suggests that 1% steel fiber is the most effective in enhancing tensile strength across all silica fume replacement levels, offering the best performance both at early and later ages. Glass fibers, despite being useful, are more appropriate for moderate improvements and when workability and cost are main considerations.

5.3. Failure patterns of specimens under compressive and tensile strength tests

5.3.1. Effect of silica fume content on failure pattern

The compressive and splitting tensile failure patterns of fiber-free geopolymer concrete specimens at 28 days with varying silica fume replacement levels (0%, 5%, 10%, and 15%) are illustrated in Figure 14. For cubic specimens, typical pyramidal failure was observed in all mixes due to the absence of fibers. However, the 10% silica fume mix demonstrated a relatively improved crack pattern, resembling fiber-reinforced concrete behavior. It is due to the stronger connection of the aggregates in the matrix and the improved interaction between the binder and aggregates.

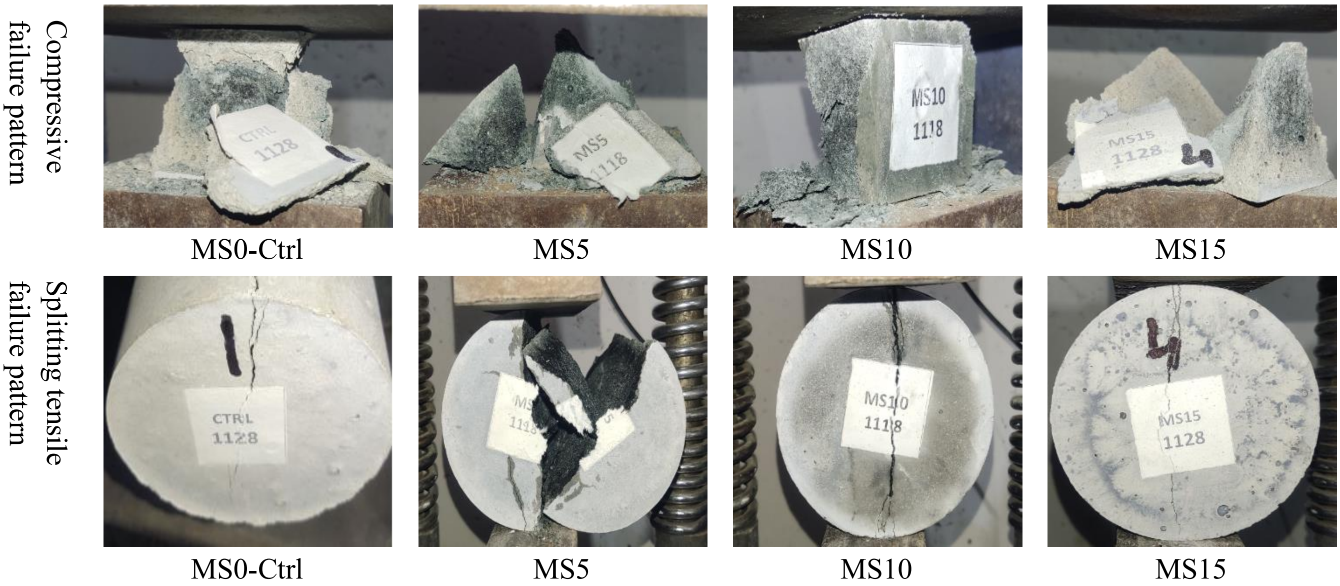


Fig. 14. Failure pattern of fiber-free HPGC after 28-day compressive strength test, showing brittle fracture and cracking.

In cylindrical specimens, deep cracks were present in the 0%, 10%, and 15% mixes, yet the failure did not lead to complete splitting, and finer cracks were more prevalent, indicating ductile behavior. In contrast, the mix with 5% silica fume exhibited the most brittle failure under both compressive and tensile loading. Specifically, under tensile testing, the specimen split completely, suggesting a loss of internal cohesion. This implies that while high-performance geopolymer concrete generally exhibits superior adhesion and crack resistance similar to fiber-reinforced concrete, a 5% replacement of slag with silica fume may disrupt this balance, resulting in a noticeable decline in fracture resistance and cohesion.

5.3.2. Effect of fiber type and content on failure pattern

The compressive and splitting tensile failure patterns of HPFRGC at 28 days are shown in Figures 15 and 16, which compare the behavior of specimens containing 0.5% steel and glass fibers. Figure 17 presents the failure patterns of specimens reinforced with 1% steel or glass fibers under both compressive and tensile loading (randomly cases).

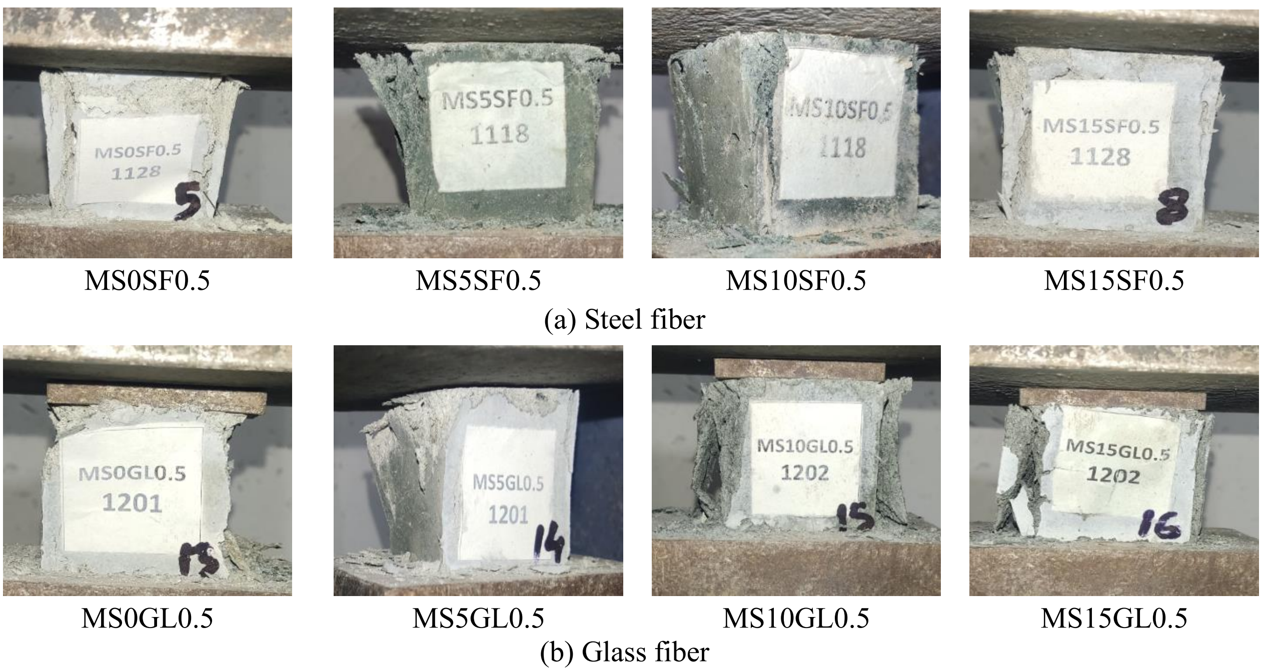
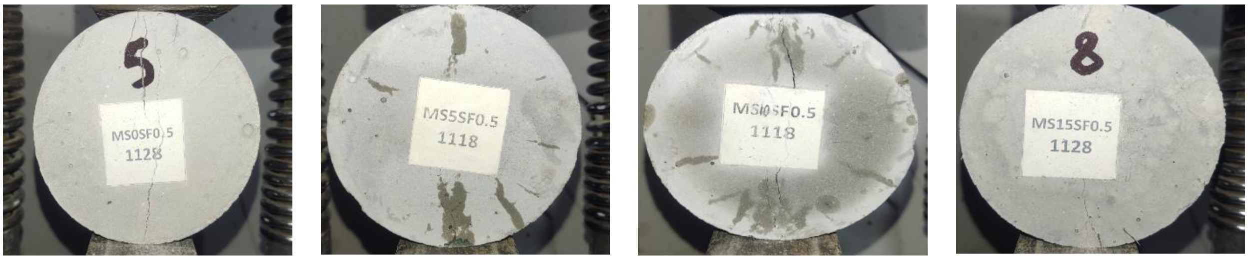
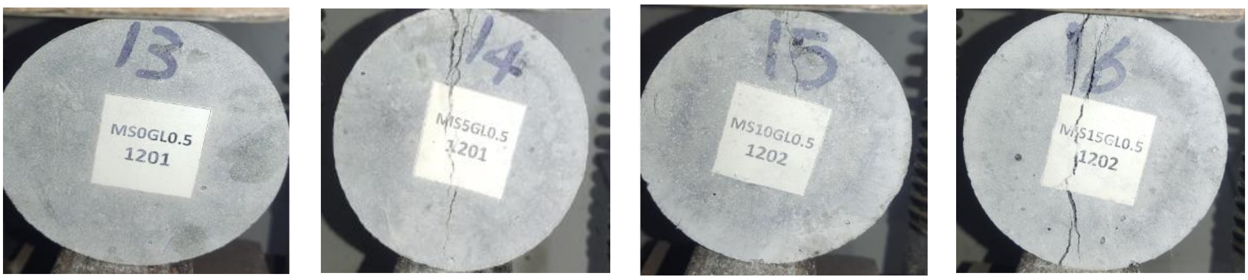


Fig. 15. Compressive failure of HPFRGC specimens at 28 days:(a) with steel fiber,(b) with glass fiber.



MS0SF0.5 MS5SF0.5 MS10SF0.5 MS15SF0.5

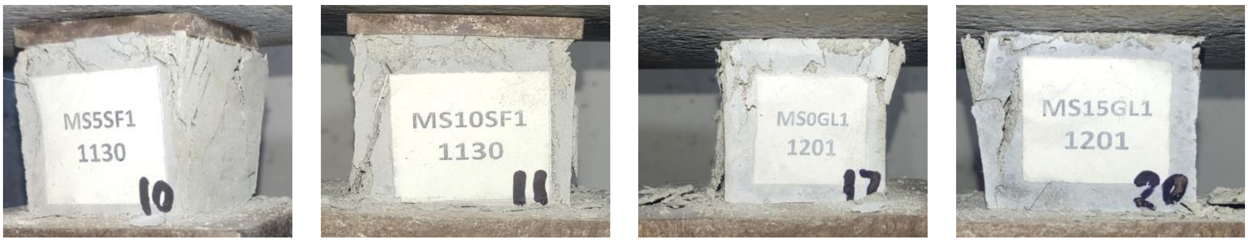
(a) Steel fiber



MS0GL0.5 MS5GL0.5 MS10GL0.5 MS15GL0.5

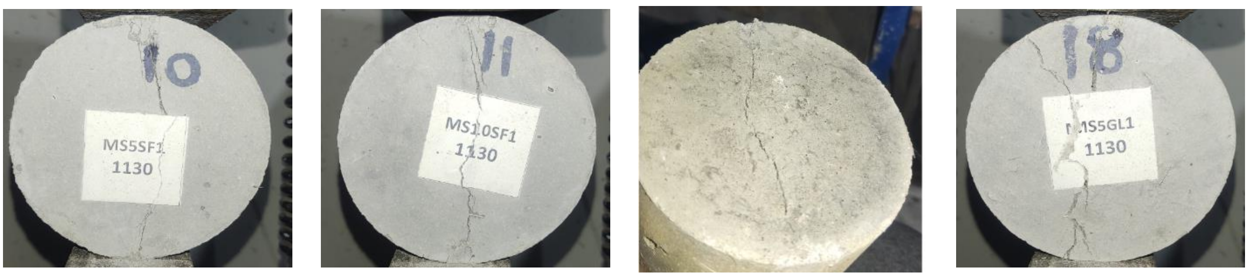
(b) Glass fiber

Fig. 16. Splitting tensile failure of HPFRGC specimens at 28 days.



MS5SF1 MS10SF1 MS0GL1 MS15GL1

(a) Compressive Failure Pattern (randomly)



MS5SF1 MS10SF1 MS0GL1 MS5GL1

(b) Splitting Tensile Failure Pattern (randomly)

Fig. 17. Failure patterns of fiber-free HPGC: (a) compressive; (b) splitting tensile.

For all fiber-reinforced mixes, the failure of the cubic specimens was characterized by the development of multiple side cracks, and no pyramidal failure was observed—unlike the typical failure mode seen in fiber-free specimens. The addition of fibers, in combination with the cohesive nature of the geopolymer matrix, effectively restrained crack propagation and improved the overall integrity of the specimens. When the fiber content was increased, the number of cracks became fewer, and the concrete became more consistent and confined under compression.

In the splitting tensile tests, deep cracks were consistently observed, but none of the cylindrical specimens split completely. Instead, a greater number of fine cracks formed, indicating enhanced post-cracking behavior and ductility due to the presence of fibers. Among the tested mixes, the specimens with 5% and 15% silica fume content in the steel fiber group, as well as the mix with 0% silica (MS0GL0.5) in the glass fiber group, exhibited the most favorable failure patterns, showing minimal crack widths. Moreover, increasing the fiber content from 0.5% to 1% did not result in a significant improvement in tensile failure behavior for either fiber type, suggesting that 0.5% fiber content may be sufficient for enhancing tensile crack control in HPFRGC.

6. Conclusions

The present research investigated the mechanical performance of slag-based high-performance fiber-reinforced geopolymer concrete (HPFRGC) incorporating different silica fume replacement levels (0%, 5%, 10%, and 15% by weight of slag), activated through mechanochemical treatment. The study focused on: (1) the effect of silica fume content on compressive and tensile strength at 7 and 28 days, (2) the influence of fiber type (steel and glass) and content (0%, 0.5%, and 1%) across binder types, and (3) the failure patterns of specimens under compressive and splitting tensile tests at 28 days. Based on the experimental findings, the following conclusions are drawn:

- Replacing slag with 5–10% silica fume improved 28-day compressive strength by up to 12.4% and tensile strength by 3.28%, due to better matrix densification and geopolymer gel formation. However, 15% replacement reduced strength, indicating that 10% silica fume is the optimal level for enhancing mechanical properties in fiber-free HPFRGC.
- Increasing fiber content from 0% to 1% significantly enhanced strength. For example, at 10% silica fume, compressive strength increased by 8.8% and tensile strength by 33% when 1% steel fiber was used. This shows that 1% fiber content, especially steel, is optimal for mechanical performance improvement.
- At the same fiber content (1%), steel fibers consistently outperformed glass fibers. At 15% silica fume, steel fibers improved compressive strength by 12.7% and tensile strength by 38.6%, compared to 6.8% and 20.5% improvements for glass fibers. It was found that steel fibers were more efficient as they had greater stiffness and bonded better with the matrix.
- Fiber-free specimens showed typical brittle failures—pyramidal fracture in cubes and complete splitting in cylinders—especially at 5% silica fume. However, 10% of silica fume improved crack behavior due to better matrix adhesion. In fiber-reinforced mixes, no pyramidal failure occurred, fibers enhanced crack resistance, reduced crack widths, and improved ductility. Notably, 0.5% fiber content was generally sufficient for effective crack control in splitting tensile failure.

Limitations and future work

This study focused on the mechanical performance of slag-based high-performance fiber-reinforced geopolymer concrete (HPFRGC) incorporating varying types and volumes of fibers as well as different silica fume replacement levels. Although the findings provide valuable insights, several limitations should be acknowledged.

First, microstructural analyses such as Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) were not conducted, which limited our understanding of the underlying mechanisms behind strength enhancement. Future studies are encouraged to incorporate such analyses to validate and complement the observed mechanical behavior.

Second, the scope of this research was limited to compressive and splitting tensile strengths. Investigating additional durability parameters such as permeability, shrinkage, freeze-thaw resistance, or long-term performance under environmental exposure would offer a more comprehensive evaluation.

Lastly, only single fiber types were assessed independently. Future work may explore the hybridization of different fiber types and their synergistic effects on both fresh and hardened properties.

These recommendations can support further development of eco-efficient and high-performance geopolymer concretes suitable for broader structural applications.

Data availability

Data will be made available on request.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Morteza Amooie: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, writing – original draft, Writing – review & editing.

Ali Sadrmomtazi: Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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