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Impact of Silica Fume on the Mechanical Characteristics of Lime-Based Lightweight Geopolymer Mortar

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Abstract

In recent years, geopolymer has been used as a cement replacement in the production of eco-friendly mortar and concrete. Most research used fly ash and slag as base materials for producing geopolymers. This work aimed to use lime as the base material for a geopolymer, with aluminum powder, to produce lightweight geopolymer mortar with different replacement levels of silica fume to enhance its properties. Many tests were done to find out the behavior of this type of mortar, such as bulk density, compressive strength, tensile splitting strength, flexural strength, and sorptivity. In addition, a statistical analysis was carried out on results after 28 days of casting. The results showed that the fresh density decreased from 1997.8 to 1783.7 kg/m3 when replacing up to 10% of lime with silica fume, and the hardened density decreased from 1896 to 1673.6 kg/m3 for the identical replacement level. Compressive, splitting tensile, and flexural strength decreased with increasing silica fume replacement level up to 10%. The sorptivity index increased with increasing silica fume replacement level.

Keywords: Aluminum Powder, Geopolymer Mortar, Lime, Mechanical Characteristics, Silica Fume.

1. Introduction

Industrialization creates and discharges unwanted pollutants into the environment. To keep up with industrialization, it is necessary to select a procedure that pollutes the environment as little as possible [1]-[4].

Producing one ton of cement requires around 2.8 tons of raw materials, including fuel and other materials, and produces 5 to 10% dust. Each ton of cement produced generates 6000 to 14000 m3 of dust, and the decarbonation of lime in the kiln releases about 1 ton of CO_2 into the atmosphere. [5], [6]. To overcome these complications, geopolymers became a viable way to use the by-products. They can be used in structural and non-structural elements and for toxic waste immobilization, with resistance to heat and harsh environments. [7], [8].

Geopolymer concrete is a comparatively new kind of concrete which is considered "green" and eco-friendly. The current objective for engineers and scientists is to develop a geopolymer with the best beneficial qualities while maintaining its environmental integrity. [9]-[11].

Geopolymers can be created using basic raw materials with high silica and alumina content. Numerous studies have demonstrated the benefits of using these constituents in concrete. The majority of the research examined the use of alkali activators that contained potassium hydroxide and potassium silicate or sodium hydroxide and sodium silicate [12]-[15].

An alkali activator solution or chemical activator is vital for initiating the geopolymerization process. While the concentration of the chemical activator strongly influences the mechanical properties of geopolymers, a strong alkaline medium is often required to enhance surface hydrolysis of the aluminosilicate particles in the raw material [16], [17].

Al-Otaibi [18] distinguished that the kind and dosage of activator utilized are predominantly important in slag-based geopolymer concrete production. Consistent with this work, increasing the activator dose and silicate modulus enhances the strength of geopolymer concrete.

Heat curing is frequently used to speed up geopolymerization and improve early-age mechanical characteristics for fly ash-based geopolymer concrete. Curing at elevated temperatures, frequently between 50 and 85 °C, can speed up the synthesis of geopolymers by encouraging the breakdown of fly ash's reactive silica and alumina. The optimal curing temperature and time depend on the properties of the fly ash, alkaline activator, and combination proportions, although a minimum heat-curing period of around 6 hours has been observed to be beneficial for producing mechanical strength. Prolonged drying or extremely high temperatures might negatively impact the resulting properties [19], [20].

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According to a study by Van Jaarsveld et al. [21] on the effect of different curing temperatures on the compressive strength of geopolymer concrete, twofold strength was attained when the curing temperature was raised to between 50 and 80 °C as opposed to the corresponding value at 30 °C. However, heat curing treatment raises costs and creates practical complications, which delay the widespread use of geopolymer concrete in situ.

Using lime powder in geopolymer concrete improves performance without heat curing. The experimentation depends on the features of daylight curing and the impact of temperature in precise oven curing. When the ideal percentage of cement and lime is added or replaced, more heat is produced. After mixing with water, the exothermic reaction can be utilized as an auxiliary for the high curing temperatures, permitting the accomplishment of the required strength at ambient temperature, which provides it a wide range of useful applications [22], [23].

Diab [24] explored the effect of adding lime to Class F fly ash geopolymer concrete under different curing conditions to develop lime–fly ash geopolymer concrete as a latent substitute for conventional fly ash geopolymer concrete. According to the findings, steam curing yielded the best mechanical performance. Specifically, adding 2% lime to steam-cured lime–fly ash geopolymer concrete produced the optimum overall mechanical characteristics and appropriate setting periods. Adding 2% lime resulted in a denser matrix and a reduced void ratio. Additionally, mechanical performance improved by increasing NaOH molarity, reducing added water content, and lowering aggregate moisture.

Tumpu and Mabui [25] looked at how hydrated lime exaggerated the workability and compressive strength of geopolymer concrete. The main binder was class C fly ash, which was activated with an alkaline solution of 8 M NaOH and Na_2SiO_3. Twenty percent of the fine aggregate was substituted with hydrated lime. Cubic specimens of 150 x 150 x 150 mm were made and either air-cured or oven-cured for 24 hours at 60 °C. At 7, 14, and 28 days, the compressive strength was assessed. The highest compressive strength at 28 days was 19.92 MPa, which was slightly less than the target strength of 20.75 MPa, according to the data. Workability was also negatively impacted by the addition of hydrated lime; the slump dropped to around 6 cm. Thus, the authors came to the conclusion that while hydrated lime can be added to geopolymer concrete, its dose and impact on strength and workability need to be carefully considered.

Khan et al. [26] studied the combined effects of SF and aluminum powder on the properties of lightweight concrete. SF was utilized as a partial replacement for ordinary Portland cement at levels of 0–20%, while aluminum powder was added at 0–0.7% as an aerating agent. The outcomes showed that aluminum powder reduced the strength and dry density, whereas SF improved the mechanical properties.

Although extensive research has explored the production of geopolymers utilizing fly ash and ground-granulated blast-furnace slag as the primary aluminosilicate precursors, comparatively limited attention has been given to the use of lime-based systems for producing lightweight geopolymer mortar. Specifically, there hasn't been enough research done on the usage of silica fume as a partial replacement material, aluminum powder as a foaming agent, and lime as a precursor. The influence of different silica fume replacement levels on the fresh, mechanical, and physical properties of lightweight lime-based geopolymer mortar therefore remains insufficiently understood. Accordingly, this work aims to address this research gap by developing lightweight geopolymer mortar based on lime and aluminum powder and systematically evaluating the effect of varying silica fume replacement levels on its performance.

2. Materials and Methods

2.1 Materials

The materials utilized in this research endeavor consisted of lime with a specific gravity of 2.7 and a bulk density of 1425 kg/m^3. Also, chemical oxide analysis confirmed that the calcium hydroxide, Ca (OH)2, content exceeded 92.5% (CaO content > 71.50%, loss on ignition, L.O.I. = 22.10%). Silica fume conforming to ASTM C1240 [27] was supplied with a specific gravity of 2.22 and a specific surface area (BET method) of 18,500 m^2/kg. Table 1 displays the chemical components of SF. Liquids of NaOH and Na_2SiO_3 were combined to create an alkaline solution. The purity of the NaOH offered in pellet form ranges from 97 to 98%. A solution having a concentration of 12 M is created by dissolving NaOH in water. Aluminum powder (99.1% metallic purity, median particle size = 45 μm, and specific surface area1.2m2/g) is also utilized to create air voids. Al-Ekhadir natural sand with a specific gravity of 2.65, bulk density of 1610 kg/m^3, that passed through a 2.36 mm sieve, fines modulus of 2.24, and water absorption of 1.15% filter was employed as a fine aggregate. To achieve the required workability, Type F superplasticizer (SP) in accordance with ASTM C494 [28] was employed.

Table 1. Chemical oxide compositions of silica fume and lime (% by mass) (the data were obtained from the supplier).

Oxide	SF	Lime
SiO_2	85	1.82
Al_2O_3	2.71	0.45
Fe_2O_3	1.31	0.28
CaO	0.45	71.50
MgO	0.55	1.12
SO_3	0.41	0.32
Na_2O	0.45	0.18
K_2O	1.52	0.21
TiO_2	0.32	0.02
L.O. I	6	22.10

2.2. Mix Proportions

Table 2 shows the mixture proportions considered in this investigation. Five combinations (solid + alkaline solution) were tested with a binder content of 1300 kg/m^3. The amount of SF that was replaced by lime varied from 0% to 10%. Flake Aluminum Powder (aluminum powder) has flat, irregular particles with a high surface-area-to-mass ratio and a particle size of around 0.5 mm. It reacts much faster and more vigorously than atomized powder; it was added at 0.04% of the

solid material content to the alkaline activator. 1.5% of SP was added to all mixes. The solid/alkaline solution ratio was 2, and the Na2SiO3/NaOH ratio was 2.

Table 2. Mix proportions of geopolymer mixes.

Mix	Binder Kg/m^3	SF %	Lime Kg/m^3	SF Kg/m^3	WG Kg/m^3	NaOH Kg/m^3	AL Kg/m^3	SP%	Sand Kg/m^3
M0	1300.0	**0.0**	866.7	0.0	288.9	144.4	0.347	1.5	350.0
M2.5	1300.0	**2.5**	845.0	21.7	288.9	144.4	0.347	1.5	350.0
M5	1300.0	**5.0**	823.3	43.3	288.9	144.4	0.347	1.5	350.0
M7.5	1300.0	**7.5**	801.7	65.0	288.9	144.4	0.347	1.5	350.0
M10	1300.0	**10.0**	780.0	86.7	288.9	144.4	0.347	1.5	350.0

2.3. Casting, Sample Preparation, And Curing Conditions

The following process was used to prepare the mixtures. Sand, SF, and lime were progressively added to the mixer bowl while the mixer rotated slowly for two minutes. The alkaline liquid, water, and SP were then added, and the mixing was continued at a slow speed. The mixing speed was raised till proficient a uniform mix was achieved. Afterward, the mortar was poured into the molds, and a vibrating table was employed to compact the fresh mix. After that, the samples were covered with a nylon sheet and left in the molds for one full day at room temperature of 23 ± 2 ºC. After 24 h, samples were demoulded and cured in an oven at 60 ºC for 24 h. After that, the specimens were left at room temperature till the time of testing.

2.4. Testing Procedures

2.4.1. Mini Slump Flow Test

The mini slump flow test was used to measure the flow of geopolymer mixes, as recommended by ASTM C1437-2015 [29].

2.4.2. Density

In accordance with ASTM C567 [30], this test was conducted on 3 samples of 50 mm cubes.

2.4.3. Compressive Strength Test

In accordance with ASTM C109/C109M [31], this test was conducted on 50 mm cubes at a load rate of 0.9 kN/s. For each combination, the average of three specimens at the ages of 7and 28 days was taken.

2.4.4. Splitting Tensile Strength Test

This test was conducted in accordance with ASTM C 496/C 496M [32]. For each combination, three 50 x 100 mm cylindrical samples were collected at 7 and 28 days, with a load rate of 0.2 kN/s. according to $F_{ct}= 2p/(\pi ld)$ where: -

F_{ct}: splitting tensile strength (MPa)

P: Maximum load at failure (N)

L: Length of cylinder (mm)

D: Diameter of cylinder (mm)

2.4.5. Flexural Strength Test

This test was conducted on 3 specimens (40×40×160) mm prisms according to ASTM C348 [33] using a loading rate of 0.05 Kn/s; three samples were tested at 28 days for each mix.

2.4.6. Sorptivity Test

Sorptivity tests are based on water flow into unsaturated concrete through large mortar pores. As a result, it is regarded as a relative permeability measurement. The sorptivity test calculates how quickly water enters concrete's pores. The average of three cylindrical discs with a 100 mm diameter and 50mm thickness, obtained from molded cylinders 100 x 200 mm, was used for this test. After being dried in an oven at around 100 ºC until they reached a consistent mass, the specimens were placed in a covered container and allowed to cool to room temperature. After that, sealing material was applied to the specimens' sides.

In order to perform the sorptivity test, the specimens were placed on glass rods in a pan so that the bottom surface of the rods was in contact with water up to a height of 3 mm. It was thought that this process would provide unrestricted water flow through the bottom surface. To calculate mass increase, the specimens were taken out of the pan and weighed at various intervals up to 64 minutes. By dividing the mass acquired by the specimen's nominal surface area and the water's density, the amount of water absorbed was determined. The test setup is shown in Fig. 1 according to ASTM C1585 [34]. These data were plotted against the square root of time. The slope of the line of best fit is the concrete's sorptivity coefficient. Here, the average of three combinations at 28 days of age was documented.

3. Results and discussions

3.1. Mini Slump Flow Test Results

Fig. 2 shows the relationship between the flow of geopolymer lightweight mortar (GLWM) and the %SF added as a partial lime replacement.

The results of the mini slump flow in Fig. 2 showed that the flow of geopolymer mixes decreased with increasing SF replacement level up to 10%. This behavior can be attributed to the increased cohesiveness and viscosity of the geopolymer mortar as SF replacement increases, which may affect particle dispersion and pore-structure development [35]. This performance may be due to the extremely high specific surface

area and amorphous nature of silica fume; water adsorption increases, leading to higher inter-particle friction and plastic viscosity. We also confirmed that despite this reduction, all flow values remained within the practical threshold for successful placement and workability [35].

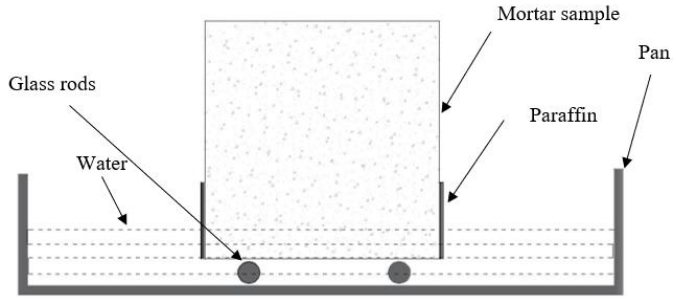

Figure 1. Sketch of Sorptivity Index.

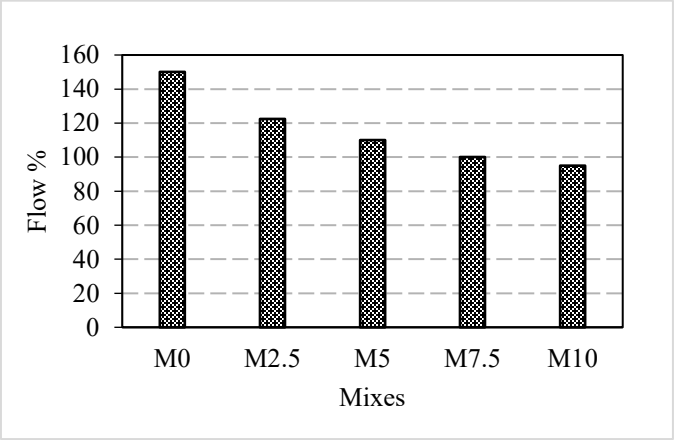

Figure 2. Slump Flow test results of geopolymer mixes.

3.2. Density

Fig. 3 shows the relationship between GLWM density and the %SF added as a partial replacement for lime.

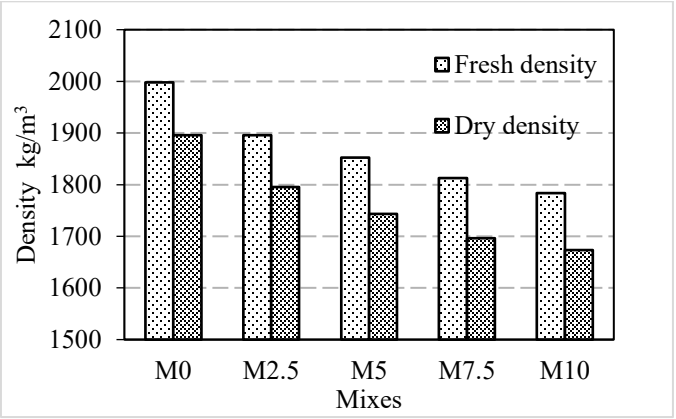

Figure 3. Density test results of geopolymer mixes.

Fig. 3 also shows that replacing SF decreases the fresh and hardened density of geopolymer mortar. The fresh density decreased from 1997.8 to 1783.7 kg/m^3 when SF replaced up to 10% of lime, and the hardened density decreased from 1896 to 1673.6 kg/m^3 for the same replacement level. This behavior may be attributed to the replacement of SF, which increases the geopolymerization reaction in the presence of aluminum powder, thereby promoting greater gas generation and pore formation within the geopolymer mortar [26].

3.3. Compressive Strength

Fig. 4 represents the relationship between the compressive strength of GLWM at 7 and 28 days and the %SF added as a partial replacement of lime.

The outcomes established that the compressive strength of all geopolymer mixes decreased with increasing SF replacement up to 10% at 7 and 28 days, as shown in Fig. 4. The decreases were (9.8, 25.6, 35.5, and 46.7) % for 2.5, 5, 7.5, and 10% SF replacement levels at 7 days, respectively, while the decreases were (9.2, 23.1, 32.3, and 38.9) % for 2.5, 5, 7.5, and 10% SF replacement levels at 28 days. These results show that, for the same mix, the decrease in compressive strength at 28 days is smaller than at 7 days as the %SF ratio increases. The decrease in compressive strength may be due to reduced geopolymer mortar density resulting from partially replacing lime with SF. The lower density indicates a more porous matrix, which can reduce the mortar's load-bearing capacity and compressive strength. The decrease in strength is not only due to reduced bulk density but may also stem from microstructural changes, where accelerated gas growth disrupts binder homogeneity, increases localized porosity, and weakens load transfer across the interfacial transition zone (ITZ). The reduction in compressive strength may be one of these reasons: 1- In the non-aerated system, silica fume particles act as pozzolanic materials that fill micro-voids and increase density; however, in the aluminum-foamed geopolymer system, silica fume accelerates the aluminum oxidation process, thereby speeding up hydrogen gas generation prior to hardening [26].

2- The use of silica fume particles increases plastic viscosity and yield stress, leading to the formation of irregularly shaped air bubbles.

3- Replacing lime with silica fume lowers the lime-to-silicate ratio, resulting in reduced wall hardness. The strength reduction was less pronounced after 28 days (a 39.0% decrease for mix M10) than after 7 days (a 46.7% decrease for mix M10). This indicates that prolonged curing allows residual silica to engage in pozzolanic reactions with dissolved calcium ions, gradually increasing the density of the cell walls separating the pores over time [36].

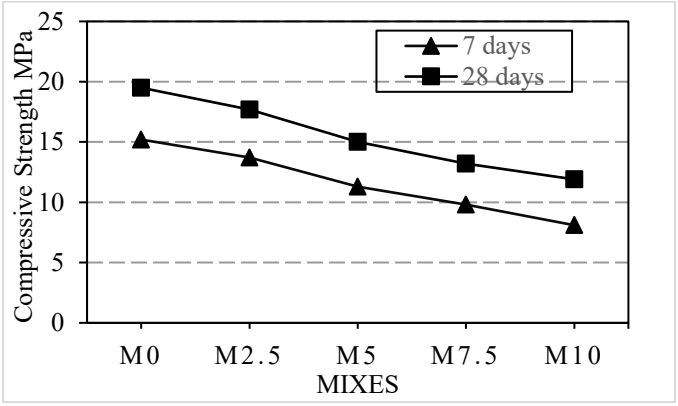

Figure 4. Compressive Strength test results of geopolymer mixes.

3.4. Splitting Tensile Strength

Fig. 5 shows the relationship between the splitting tensile strength of GLWM and the %SF added as a partial lime replacement.

The outcomes confirmed that the splitting tensile strength of all geopolymer mixtures decreased with increasing %SF replacement up to 10% at 7 and 28 days, as described in Fig. 5. The decreases were (7.1, 14.3, 23.8, and 28.5) % for 2.5, 5, 7.5, and 10% SF replacement levels at 7 days, respectively, while the decreases were (6, 14, 22.4, and 28) % for 2.5, 5, 7.5, and 10% SF replacement levels at 28 days. These results also show that, for the same mix, the decrease in splitting tensile strength at 28 days is smaller than at 7 days as the SF ratio increases. The observed decrease in splitting tensile strength may be attributed to reduced geopolymer mortar density resulting from partial replacement of lime with SF. For the same reason mentioned above (in the compressive strength paragraph), this leads to a decrease in splitting tensile strength.

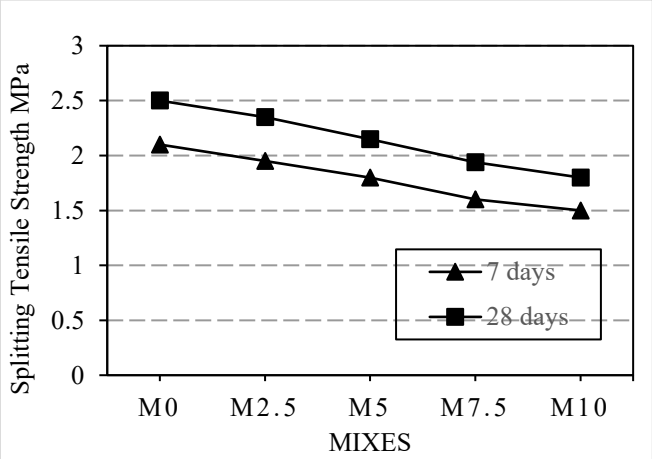

Figure 5. Splitting Tensile Strength test results of geopolymer mixes.

3.5. Flexural Strength

Fig. 6 shows the relationship between the flexural strength of GLWM and the %SF added as a partial lime replacement. The outcomes confirmed that the flexural strength of all geopolymer mixtures decreased with increasing %SF replacement up to 10% at 28 days, as calculated in Fig. 6. The decreases were (10.3, 15.7, 22.8, and 31.4) % for 2.5, 5, 7.5, and 10% SF replacement levels at 28 days, respectively. The observed decrease may be due to reduced geopolymer mortar density resulting from partial replacement of lime with SF. For the same reason mentioned above (in the compressive strength paragraph), this leads to a decrease in flexural strength.

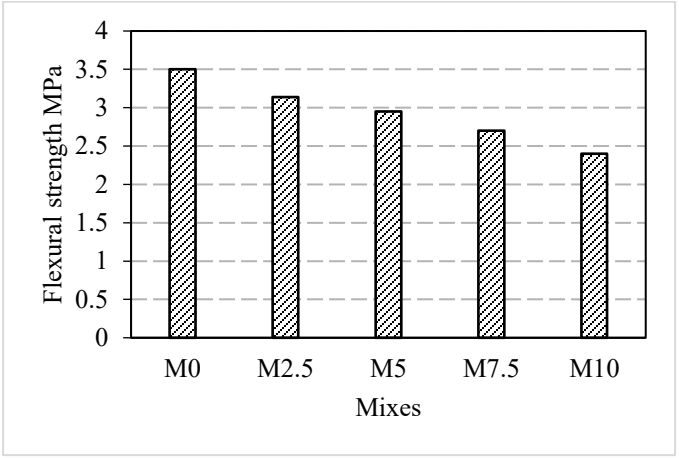

Figure 6. Flexural Strength test results of geopolymer mixes.

3.6. Sorptivity Index

Fig. 7 represents the relationship between the sorptivity index tests of GLWM with the %SF added as a partial replacement of lime.

The results confirmed that the sorptivity of all geopolymer mixes increased with increasing SF replacement ratio up to 10% at 28 days, as revealed in Fig. 7. The increases were (9, 15.1, 21.2, and 25.4) % for 2.5, 5, 7.5, and 10% SF replacement levels at 28 days, respectively. The increase may be due to a decrease in the density of geopolymer mortar when lime is replaced by SF. The increase in sorptivity index reflects a transition toward a more open, interconnected capillary pore network. While density decreases, the connectivity and tortuosity of the pores govern fluid transport, indicating that higher SF replacement—while promoting aeration—facilitates capillary suction channels.

4. Statistical Analysis

The Statistical Package for the Social Sciences (SPSS) (2019) [37] program was used to detect the effect of different groups (mixtures) on the study parameters. Least squares comparison between means (ANOVA) was used. This study calculated correlation coefficients between the different variables. Note that these relations were based on tests carried out at 28 days only. Table 3 showed that mixture proportion affected the mechanical and sorptivity properties of the tested specimens. In general, increasing the SF content from M0 to M10 gradually reduced compressive, tensile, and flexural strengths, while sorptivity increased. However, the statistical significance of these changes varied among the investigated properties.

Table 3. Effect of Mixture on different properties of GLWM

Mix.	M0	M2.5	M5	M7.5	M10	LSD(P-value)
Mean ±SE of Comp. strength (Mpa)	19.50 ±0.63	17.70 ±0.52	15.07 ±0.58	13.20 ±0.81	11.90 ±0.86	2.438 ** (0.0001)
Mean ±SE of Tensile strength (Mpa)	2.50 ±0.63	2.35 ±0.63	2.15 ±0.08	1.95 ±0.60	1.8 ±0.79	1.293 NS (0.8231)
Mean ±SE of Flexural strength (Mpa)	3.50 ±1.15	3.14 ±0.49	2.95 ±0.59	2.70 ±1.21	2.40 ±0.52	1.699 NS (0.9097)
Mean ±SE of Sorptivity ($g/mm^{2/min1/2}$)	0.0986 ±0.007	0.1075 ±0.008	0.1135 ±0.008	0.1195 ±0.009	0.1236 ±0.008	0.0221 * (0.0415)

4.1. Compressive Strength

The mixture proportion had a highly significant effect on compressive strength, with a P-value of 0.0001**,** indicating that the differences among the mixtures were statistically significant at the 1% probability level. The mean compressive strength decreased progressively from 19.50 MPa for M0 **to** 17.70, 15.07, 13.20, and 11.90 MPa for M2.5, M5, M7.5, and M10, respectively.

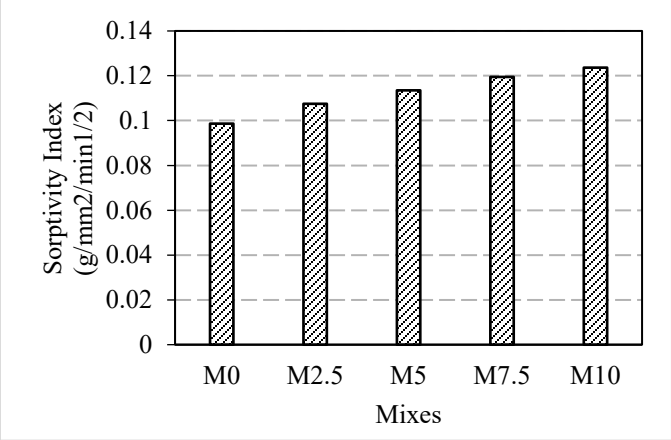

Figure 7. Sorptivity index test results of geopolymer mixes.

Compared with the M0, the M10 mixture exhibited a reduction of approximately 39% in compressive strength. The LSD results indicate that M0 and M2.5, which shared the same statistical group letter, were not significantly different, whereas greater mixture proportions generally resulted in significant reductions in compressive strength. This indicates that compressive strength was particularly sensitive to increasing the mixture proportion.

The reduction in compressive strength may be associated with changes in the internal structure and bonding characteristics of the mixture as the proportion of SF increased. However, the present results alone do not establish the exact mechanism responsible for this reduction.

4.2. Tensile Strength

A gradual reduction in tensile strength was also observed as SF increased. The mean tensile strength decreased from 2.50 MPa at M0 **to** 1.56 MPa at M10, representing an approximate reduction of 38%.

Despite this apparent downward trend, the effect **was** not statistically significant, as indicated by the P-value of 0.8231; therefore, although the mean values suggest that increasing the SF proportion may reduce tensile strength, the effect was not statistically significant.

4.3. Flexural Strength

Flexural strength followed a similar decreasing trend. The mean flexural strength decreased from 3.50 MPa for M0 **to** 3.14, 2.93, 2.70, and 2.40 MPa for M2.5, M5, M7.5, and M10, respectively.

The reduction between the control mixture and M10 was approximately 31%. Nevertheless, differences among the mixtures were not statistically significant (P = 0.9097)**.**

4.4. Sorptivity Test

In contrast to the mechanical properties, sorptivity increased as SF proportion increased. The mean sorptivity increased from 0.0986 g/mm²/min$^{1/2}$ for M0 **to** 0.1236 g/mm²/min$^{1/2}$ for M10, representing an increase of approximately 25%.

The effect of the SF proportion on sorptivity was statistically significant, with a P-value of 0.0415, indicating significance at the 5% probability level. According to the LSD grouping, M0 and M10 belonged to different statistical groups. This indicates that the most pronounced statistically significant difference occurred between the control and the highest SF proportion.

The increase in sorptivity suggests that increasing the SF proportion was associated with greater water uptake. This behavior may indicate changes in the internal structure that do not facilitate water penetration.

4.5. Correlation among the Investigated Properties

From Table 4, the correlation analysis provides additional information about the relationships among the measured properties. A positive and statistically significant correlation was observed between compressive strength and tensile strength (r = 0.41, P = 0.0492). This indicates that mixtures with higher compressive strength tended to exhibit higher tensile strength, although the correlation was moderate rather than strong.

The correlation between compressive and flexural strengths was positive (r = 0.25) but statistically non-significant (P = 0.3673).

The strongest correlation was observed between compressive strength and sorptivity, with a negative correlation coefficient of r = −0.71 and a P-value of 0.0100. This represents a relatively strong inverse and statistically significant relationship, indicating that specimens with higher compressive strength tended to have lower sorptivity values.

Similarly, tensile strength showed a significant negative correlation with sorptivity (r = −0.52, P = 0.0356). In contrast, the correlation between flexural strength and sorptivity was negative but statistically non-significant (r = −0.33, P = 0.2347**)**.

Table 4. Correlation coefficient between different variables.

Variables		Correlation coefficient (r)	P-value
Compressive strength	Tensile strength	0.41 *	0.0492
	Flexural strength	0.25 NS	0.3673
	Sorptivity	-0.71 **	0.0100
Tensile strength	Flexural strength	0.15 NS	0.5888
	Sorptivity	-0.52 *	0.0356
Flexural strength	Sorptivity	-0.33 NS	0.2347

* (P≤0.05), ** (P≤0.01).

5. Conclusions

1- The incorporation of SF leads to an enhanced geopolymerization reaction in lime-based geopolymer mortar containing aluminum powder, thus promoting increased gas generation and pore formation. The resulting increase in pore

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volume and porosity contributes to a reduction in the bulk density of the resulting lightweight geopolymer mortar.

2- The compressive strength decreased with increasing levels of SF replacement. This reduction is attributed to the reduction in the density of the geopolymer mortar accompanying the partial replacement of lime by SF. The subsequent increase in porosity and pore volume may have weakened the hardened matrix, thereby contributing to the detected reduction in compressive strength.

3- The results indicated that the reduction in compressive strength with increasing SF replacement levels was less distinct at 28 days than at 7 days. This behavior is attributed to the continued geopolymerization and progressive development of the binder matrix during extended curing, which may have partially compensated for the strength reduction related to the increased SF content.

4- The splitting tensile and flexural strengths revealed trends consistent with those for compressive strength, with both mechanical properties reducing progressively as the SF replacement ratio increased.

5- The sorptivity of all geopolymer mortar mixtures increased progressively with increasing SF replacement levels, attaining its highest value at a 10% SF replacement level.

6- From statistical analysis, the outcomes show that increasing the SF proportion from M0 to M10 generally reduced the measured mechanical strength properties while increasing sorptivity. The effect was particularly pronounced and statistically significant for compressive strength**,** whereas the reductions in tensile and flexural strengths were not statistically significant. Conversely, sorptivity increased significantly with increasing SF proportion.

7- The correlation analysis further supports the observed relationship between mechanical performance and sorptivity behavior, particularly through the relatively strong inverse correlation between compressive strength and sorptivity.

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Ali Kadhim: proposed the research problem. Authors Ali Kadhim & Osamah Mohammed: developed the theory and performed the computations. Mohammed Zohair: Supervised the findings. Authors Ali Kadhim & Osamah Mohammed: Discussed the results and contributed to the final manuscript.

Use of LLM and AI

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