Revue des Composites et des Matériaux Avancés-Journal of Composite and Advanced Materials
Vol. 36, No. 1, February, 2026, pp. 175-182
Journal homepage: http://iieta.org/journals/rcma

Synergistic Effects of Fly Ash and Silica Fume on the Mechanical and Durability Performance of Metakaolin-Based Geopolymer Concrete

Hussein K. Khalaf[1], Samer S. Abdulhussein[1*], Aous A. Moyet[2], Israa M. Abbas[3], Ala Z. Keblawi[4]

[1] Department of Civil Engineering, College of Engineering, Mustansiriyah University, Baghdad 10045, Iraq
[2] Department of Civil Engineering, University of Baghdad, Baghdad 10071, Iraq
[3] Oil Exploration Company, Ministry of Oil, Baghdad 10045, Iraq
[4] Department of Civil Engineering and Sustainable Structures, Palestine Technical University–Kadoorie, Tulkarm P305, Palestine

Corresponding Author Email: samersaeed@uomustansiriyah.edu.iq

https://doi.org/10.18280/rcma.360117

Received: 26 November 2025
Revised: 8 February 2026
Accepted: 20 February 2026
Available online: 28 February 2026

Keywords:
geopolymer concrete, fly ash, silica fume, metakaolin, mechanical properties, sustainability, water absorption

ABSTRACT

This study explores the synergistic effects of fly ash and silica fume on the mechanical properties and durability of metakaolin-based geopolymer concrete (MGC). Seven mix designs, incorporating varying combinations of fly ash and silica fume, were evaluated for their impact on concrete strength and water absorption. The results showed that the combined use of fly ash and silica fume led to a significant improvement in the mechanical performance and durability of the concrete compared to mixes using individual materials. The optimal performance was achieved with the mix containing the highest levels of both materials, which showed enhanced compressive strength from 44.2 Mpa for M6 compared to 32.5 Mpa for the reference mix and reduced water absorption from 6.8% to 4.3%. This study provides valuable insights into the development of high-performance, sustainable geopolymer concrete with enhanced durability.

1. INTRODUCTION

The construction sector is famously attributed to being one of the largest contributors of carbon dioxide emissions and the utilisation of natural resources worldwide. This is largely because it consumes a large amount of Ordinary Portland Cement (OPC). Recent findings have indicated that the cement industry contributes a significant portion of CO_2 emissions throughout the world because it consumes a considerable amount of energy to process cement and also requires a lot of raw materials [1, 2]. In addition to these environmental issues, current infrastructure development efforts require stronger, durable, and capable materials to withstand extreme conditions. At the same time, the rapid development of materials science supported by data-driven and computational analysis is changing the design, optimisation, and evaluation of concrete and binder systems [3]. With the development of geopolymer technology, there has been an increased focus on researching how the effectiveness of geopolymer binders can be enhanced through proper mix design and material engineering. Recent studies on the subject of geopolymer concrete have again emphasised that the macro properties of the concrete mix can be controlled by the chemistry of the binder system, the reactivity of the aluminosilicate precursors, and the development of the geopolymer gel structure. It has been established that by controlling all of the above parameters, the strength of the concrete can be enhanced, the porosity reduced, and the sustainability of the mix increased. In other words, the effectiveness of the binder can be enhanced without compromising the environment [4]. Recent studies have shown that the macroscopic mechanical performance of geopolymer concretes is strongly influenced by binder chemistry, reaction kinetics, and gel structure development. [5, 6]. In this bigger picture, an increasing number of individuals are eager to become acquainted with materials at the micro- and nano-scales and develop improved tools to characterise materials capable of relating microstructural aspects to macroscopic mechanical behaviour and durability. Recent surveys have highlighted the necessity of micro-resolved crystochemical and mechanical probes in the future of sustainable cement-based and other binder technologies [7]. The search for more sustainable aggregates and binder systems, with the inclusion of unusual materials such as sea sand and recycled material, underlines the growing need to see the issue of sustainability in construction materials engineering as a complex concept that must be addressed [8].

Geopolymer materials have become a new breed of low-carbon binders made by the alkali activation of silicate-rich materials containing aluminosilicate. They can be considered one of the most promising alternatives to OPC. Comprehensive tests have demonstrated that geopolymers can achieve mechanical and durability properties that are only similar to or even better than those of conventional cement-based systems and offer considerable environmental benefits owing to lower CO_2 emissions and waste valorization [9]. Even though they have performed remarkably well in the laboratory, transferring lab research to reliable and cost-effective production of geopolymer materials in industrial life remains one of the biggest issues [10].

From a materials engineering perspective, continued efforts have been made to improve the performance of geopolymer concrete by incorporating supplementary cementitious materials (SCMs). Silica fume (SF) have also been widely reported to be effective additives for increasing the mechanical strength, densification of the microstructure, and durability of geopolymer systems [11]. Simultaneously, more general intentions to handle waste and better utilize resources using alkali-activated geopolymer binders have been viewed as a significant way to make the building process more sustainable [12].

The performance of geopolymer concretes is highly dependent on early age reaction mechanisms and curing conditions, which directly influence the durability of the materials [13]. Geopolymer concrete has also been considered extensively in applications that require superior resistance to fire and high temperatures. It has excelled in these aspects compared to conventional OPC-based systems [14]. These reasons make geopolymer technology an even better option for the infrastructure of the future because it can perform numerous actions and performs very well.

Recent extensive analyses have also revealed the significance of creating new low-carbon and high-performance cement-based and alternative binder composites to enable the world to achieve its sustainability targets [15]. Bibliometric analyses conducted recently have revealed that the use of MK-based geopolymers is one of the most dynamic and active fields of research [16]. This is because MK-based systems have received significant interest in the family of materials of geopolymers. Metakaolin-based geopolymer concrete (MGC) is generally considered highly reactive, has a high-density microstructure, grows rapidly in strength, and is highly chemically stable.

Nevertheless, the issue of larger-scale concerns with construction sustainability, energy efficiency, and structural resilience continues to hinder the adoption of metakaolin-based geopolymer systems, in particular, as far as retrofitting and upgrading old buildings are concerned [17]. Moreover, even though geopolymer concretes have shown better mechanical and durability properties, research is being conducted on how to further enhance their performance, such as the incorporation of fibers and other functional additives [18].

Recently, there has been increased interest in the application of nanomaterials and multiscale modifiers to make geopolymer concretes stronger, longer lasting, and more functional. Systematic reviews have proven that nanomaterials can significantly increase the microstructure, interfacial bonding, strength, and durability, but there are still certain practical and economic concerns to be addressed [19]. At the same time, it has been found that advanced soft computing and machine learning algorithms are gradually being utilized in predicting the compressive strength and overall performance of geopolymer concretes, which highlights the need to generate high-quality experimental data to ensure reliability in developing models and validating them [20].

The present study is an attempt to understand the synergistic effect between fly ash (FA) and silica fume on MGC, which has remained unclear. Unlike previous studies, where each individual admixture has been investigated either independently or under varying conditions, the present study aims to understand the effect of synergy between both admixtures by maintaining a constant aggregate gradation, activator composition, and curing regime for all mixes.

The results reveal that the concurrent use of both admixtures has a synergistic effect on improving the mechanical properties and durability, which is nonlinear and surpasses the cumulative effect of both admixtures used individually. This improvement is attributed to microstructural densification and the development of a continuous N–A–S–H gel phase, as evidenced by SEM analysis.

The present study successfully established a relationship between binder synergy, microstructural development, and macro-properties, thereby offering a deeper insight into the behavior of ternary MGC. The results provide a scientific direction for the development of high-performance and sustainable geopolymer concretes with minimal adverse impacts on the environment.

2. METHODOLOGY

Metakaolin was prepared using natural kaolinite clay from deposits in the Iraqi governorate of Al-Anbar. Raw kaolin was heated in a laboratory muffle furnace for three–four hours at 700°C to obtain highly amorphous and reactive metakaolin. The final product was produced by processing local Iraqi deposits in the laboratory. The chemical composition, according to X-ray fluorescence (XRF) analysis, was approximately 53% SiO_2, 44% Al_2O_3, 0.8% Fe_2O_3, and 1.6% TiO_2. The physical properties were a specific gravity of 2.56, a Blaine fineness of about 1000 m²/kg, and a median particle size (D50) of about 2.5 µm. Microstructural and mineralogical characterisation by X-ray diffraction (XRD) and scanning electron microscopy (SEM) of dehydroxylation and amorphization success is through finding irregular plate-like particles and the lack of crystalline kaolinite peaks.

Class F fly ash, supplied by the South Baghdad Thermal Power Plant, was supplied by the Iraqi Ministry of Electricity with a specific gravity of approximately 2.3 and a median particle size of approximately 15 µm. Although the CaO content was approximately 6.8% and the loss on ignition was approximately 2.5%, the combined content of SiO_2, Al_2O_3, and Fe_2O_3 exceeded 72%. Elkem ASA (Norway) supplied silica fume, which Sika Iraq marketed in the country. Having an average particle size of 0.1-0.3 µm, a specific gravity of 2.22, and a BET surface area of approximately 18-20 m²/g, over 92% of it consisted of amorphous SiO_2.

Fine aggregate: The natural river sand of Baghdad, Al-Taji Quarry of Iraq, was used as the fine aggregate. Its specific gravity, water absorption, and fineness modulus were 1.2, 2.63, 1.2, and 2.65, respectively. The coarse aggregate was the Al-Nibaie Quarry in Baghdad, Iraq, and was composed of crushed granite with an approximate maximum nominal size of 19 mm. The coarse aggregate contained 0.7% of water, and its specific gravity was 2.67.

The alkaline activator comprised solutions of sodium hydroxide and sodium silicate. Analytical-grade 98% pure sodium hydroxide pellets from Merck, Germany, were used to prepare a solution. The solution of sodium silicate (PQ

Corporation, Belgium) had a silica modulus (SiO_2/Na_2O) of 3.2, and a chemical composition of 28.7% SiO_2, 8.9% Na_2O, and 62.4% H_2O. Sika Iraq supplied Sika ViscoCrete-5930, which is a polycarboxylate ether (PCE)-based superplasticizer, to improve the workability of the fresh geopolymer concrete at a constant dosage rate of 0.8% of the binder weight.

To design the seven geopolymer concrete mixtures, a constant total binder content of 450 kg/m³ was used. The sodium silicate to sodium hydroxide ratio was maintained at 2.1, and the activator-to-binder ratio was maintained at 0.60. The levels of course and fine aggregates were maintained at 1050 kg/m³ and 650 kg/m³, respectively. In the reference mixture, 100% metakaolin was used as the binder, whereas in the other mixtures, fly ash and/or silica fume were used in different proportions to partially replace the metakaolin (Table 1).

Table 1. Mix proportions of metakaolin-based geopolymer concrete (MGC) (kg/m³)

Mix ID	Metakaolin (kg/m³)	Fly Ash (kg/m³)	Silica Fume (kg/m³)
M0	450	0	0
M1	360	90	0
M2	315	135	0
M3	405	0	45
M4	382.5	45	22.5
M5	337.5	90	22.5
M6	315	90	45

The mix proportion design was established with the aim of evaluating the individual and combined effects of fly ash and silica fume on MGC. The proportion of fly ash replacement, ranging from to 20-30%, and silica fume replacement, at 10%, were selected on the basis of the optimum ranges of replacement that have been established in previous studies. Studies have confirmed that the addition of fly ash and silica fume is effective for enhancing the reactivity of geopolymer concrete. In addition, trial mixes were prepared to ensure that adequate workability was maintained and that there was no excessive dilution of the metakaolin content. The total content of the binder, aggregate size distribution, activator content, and curing were maintained constant. This was done with the aim of isolating the combined effect of fly ash and silica fume on the properties of MGC.

The dry products were initially mixed in a pan mixer to ensure a uniform distribution of all the dry products involved, such as metakaolin, fly ash, silica fume, sand, and coarse aggregate. The mixture was then mixed again with the superplasticizer and the alkaline activator solution that had been prepared 24 h prior to the addition of the mixture, and then it continued until the mixture was homogenous and workable. Then, the new geopolymer concrete was placed in steel molds. Flexural strength tests were performed using prism specimens (100 mm × 100 mm × 500 mm), and splitting tensile strength tests were performed using cylindrical (150 mm diameter and 300 mm height) and cube (100 mm × 100 mm × 100 mm) specimens. The molds were layered in two layers and compressed using a vibrating table to eliminate any trapped air and ensure good consolidation.

All specimens were tightly sealed with a plastic film to prevent moisture loss and cured in an oven at 60°C for 24 h. After oven curing, the specimens were demolded and stored under ambient laboratory conditions (25 ± 2°C) until testing.

Compressive strength tests were conducted on 28 days old 100 mm cube specimens at loading rate of 0.6–0.2 MPa per second up to failure in compliance with BS EN 12390-3 [21]. The splitting tensile strength was determined using 150 300 mm diameter cylindrical specimens that were tested at 28 d, as prescribed in ASTM C496 [22]. Plywood-bearing strips were used to apply the load diametrically. The flexural strength was determined as the 100 × 100 × 500 mm prism samples were measured at 28 days with a third-point loading setup with a clear span of 400 mm and tested in accordance with ASTM C78 [23, 24]. The dry mass of the specimens was obtained by drying the samples in ovens at 105°C to a constant mass, followed by submerging the samples in water and in the dry, saturated, and suspended states to obtain water absorption and apparent porosity as per ASTM C642 [25].

Scanning electron microscopy (SEM) of the geopolymer concrete mixtures was used to determine the microstructural properties of the geopolymer concrete mixtures. The specimens were dried and coated with gold to ensure that they were conductive to the surface before high vacuum and an accelerating voltage of 10-15 kV were applied. Microstructural observations indicated that the addition of fly ash and silica fume to the geopolymer matrix gradually increased its density. The mixtures containing fly ash showed partially reacted spherical particles surrounded by a growing N-A-S-H gel, and the reference mixture showed unreacted metakaolin plates and open pores. The mixture containing the highest combined content of fly ash and silica fume presented a continuous and homogenous gel mass that was dense and showed a high level of geopolymerization. Silica fume also added fineness to the pore structure.

To establish the importance of the variations observed in the mixtures, the results were subjected to statistical evaluation. The mean value of the three tested samples was used for the results. It was also important to ensure the consistency of the results, which was performed by calculating the standard deviation and coefficient of variation. For the results, one-way analysis of variance (ANOVA) was performed at a 95% confidence level, which is equivalent to $p < 0.05$. The mixtures containing fly ash and silica fume were observed to increase their strength, as shown by the results. It was also observed that the greater the amount of material, the better the results, as indicated by the reduced variation. This shows that the improvements were not due to experimental variations.

3. RESULTS AND DISCUSSION

This chapter presents and discusses the findings of mechanical and durability tests conducted on MGC that uses FA and silica fume. The main properties measured were the compressive strength, splitting tensile strength, flexural strength, and water absorption. The results are summarised in Table 2. In general, the findings revealed that the incorporation of fly ash and silica fume enhanced the performance of the MGC compared to that of the reference mix (M0). Fly ash was useful for long-term strength improvement and durability, whereas silica fume was useful for improving the early strength and refining of pores. Moreover, mixtures that consisted of a combination of the two SCMs throughout the measurements showed optimal performance against all the parameters measured, implying the possibility of a synergistic effect that optimizes the balance between permeability and strength.

A specific detailed description of each property is provided in the sections below, and the manner in which fly ash and silica fume influence the durability and mechanical behaviour of MGC is highlighted.

3.1 Discussion of compressive strength

The compressive strength results of the MGCs are presented in Table 2. The compressive strength of the reference mix M0 was found to be 32.5 MPa. This proves the high reactivity of metakaolin. However, the SEM micrographs of the reference mix M0 indicated the presence of partially reacted metakaolin plates and a porous geopolymer gel. The compressive strength of geopolymer concretes containing silica fume was significantly enhanced. The compressive strength of the geopolymer concretes containing individual and combined SCMs varied depending on the replacement level. Mix M1, which contained 20% fly ash, and mix M4, which contained a total replacement of 15% (10% fly ash and 5% silica fume), exhibited compressive strengths of 39.7 MPa and 41.0 MPa, respectively. The enhancement of the compressive strength is due to the microfiller effect of silica fume. In addition, the high content of amorphous silica in the silica fume also contributes to the enhancement of the compressive strength. The SEM micrographs of the geopolymer concretes containing silica fume indicated a dense N–A–S–H gel structure.

The addition of fly ash (M2 and M5) was also found to contribute to strength development. However, this effect was less prominent for the individual addition of fly ash. SEM analysis for the addition of fly ash to the geopolymer paste showed the presence of unreacted spherical fly ash particles in the geopolymer paste. This supports the long-term strength development through the gradual geopolymerization process.

For the blended mixtures (M3 and M6), which contained both fly ash and silica fume, the highest compressive strength was achieved. The highest compressive strength of 44.2 MPa was recorded for the blend mixture (M6). This indicated a synergistic effect between the two supplementary materials. The combined addition of silica fume and fly ash resulted in the development of a highly compact and homogeneous microstructure. This is evident from the absence of interconnected voids in the microstructure. In addition, the formation of a continuous N–A–S–H geopolymer gel network was observed in the microstructure.

3.2 Discussion of splitting tensile strength

The splitting tensile strengths of the MK-based geopolymer concrete (MGC) mixes are presented in Table 2. The reference mix M0 recorded a tensile strength of 2.4 MPa. This was attributed to the brittle nature of the geopolymer matrix, microvoids, and weak interfacial zones. These microstructural features were evident in the SEM micrographs of the corresponding mix. The addition of silica fume to the geopolymer matrix resulted in an enhanced splitting tensile strength of 3.0 MPa for mix M4. The enhancement of the tensile properties is attributed to the refinement of the interfacial transition zone between the aggregate and geopolymer matrix. The ultrafine silica fume particles improved the particle packing density of the geopolymer matrix. This results in the formation of a dense N–A–S–H gel at the aggregate-matrix interface, thus enhancing the tensile properties of the geopolymer concrete. The fly ash-based geopolymer concrete mixes M2 and M5 recorded moderate tensile strengths ranging from 2.6 MPa to 2.7 MPa. The SEM micrographs of the corresponding mixes show partially reacted spherical fly ash particles dispersed in the geopolymer matrix. The partially reacted fly ash particles improved the density of the geopolymer matrix. This results in an enhancement of the tensile properties. The blended fly ash-silica fume-based geopolymer concrete mixes M3 and M6 recorded the highest splitting tensile strength. The tensile strength recorded for mix M6 is 3.3 MPa. The enhancement of the tensile properties is attributed to the synergistic effect of the addition of fly ash and silica fume. The addition of silica fume improved the early age interfacial zone of the geopolymer matrix. The addition of fly ash improved the density of the geopolymer matrix. The addition of fly ash and silica fume resulted in a compact and homogeneous microstructure. The compact and homogeneous microstructure of the geopolymer matrix improved the tensile properties of the geopolymer concrete. The homogeneous microstructure of the geopolymer matrix delayed the onset of cracks and restricted their growth.

Table 2. Mechanical properties and water absorption results of metakaolin-based geopolymer concrete (MGC) mixes at 28 days (mean ± SD)

Mix ID	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Flexural Strength (MPa)	Water Absorption (%)
M0	32.5 ± 0.9	2.4 ± 0.1	4.3 ± 0.2	6.8 ± 0.2
M1	39.7 ± 1.1	2.9 ± 0.2	5.1 ± 0.2	5.2 ± 0.3
M2	34.8 ± 1.0	2.6 ± 0.2	4.7 ± 0.3	6.1 ± 0.2
M3	42.3 ± 1.2	3.1 ± 0.2	5.5 ± 0.3	4.6 ± 0.3
M4	41.0 ± 1.1	3.0 ± 0.1	5.4 ± 0.1	5.0 ± 0.4
M5	36.5 ± 1.0	2.7 ± 0.1	4.9 ± 0.2	5.8 ± 0.3
M6	44.2 ± 0.8	3.3 ± 0.2	5.8 ± 0.1	4.3 ± 0.2

3.3 Discussion of flexural strength

The flexural strength test results for the MGC mixes are presented in Table 2. The reference mix (M0) recorded a flexural strength of 4.3 MPa. This can be attributed to the limited ability of the geopolymer matrix to withstand cracks. This was due to the brittle nature of the geopolymer matrix. The matrix contained discontinuities in the microstructure. When subjected to a bending load, the matrix is more prone to the formation of microcracks. This limits the efficiency of stress transfer in the matrix.

Addition of silica fume in mix M4 led to an increase in flexural strength, although mixes with silica fume, especially the M3, M4, and M6, have improved flexural overall performance. The flexural strength values recorded were 5.5 MPa in the case of M3, 5.4MPa in the case of M4, and 5.8 MPa in the case of M6 as compared to the reference mix of 4.3Mpa. The enhancement can be explained by the fact that the fume particles of silica are ultrafine, which causes the densification of the matrix and the increase in the load transfer capacity. The results of SEM observations established that silica fume encouraged a smaller geopolymer structure and less development of microcracks.

The addition of fly ash to the geopolymer matrix in mixes M2 and M5 resulted in a moderate improvement in the flexural strength. The recorded strength values ranged from 4.7 to 4.9 MPa. This improvement in the mechanical performance may be attributed to the efficiency of the geopolymer matrix in the transfer of load. This efficiency can be attributed to the limited formation of cracks in the matrix. This may be attributed to the effect of fly ash. The gradual reaction of the fly ash resulted in partial densification of the matrix. This inhibits the formation of microcracks in the matrix. The addition of a blend of fly ash and silica fume to the geopolymer matrix in mixes M3 and M6 resulted in the highest recorded flexural strength. The recorded strength values were 5.8 MPa. This may be attributed to the effect of blending the two supplementary materials. The addition of these two materials to the geopolymer matrix resulted in a more compact matrix. This matrix inhibited the formation of microcracks in the matrix. This resulted in an improvement in the mechanical performance.

3.4 Discussion of water absorption

The water absorption results of the MGC mixes are shown in Table 2. The reference mix M0 has a relatively high water absorption of 6.8%, which is associated with the inherent porosity of the MK-based geopolymer materials. The SEM micrographs indicated an open pore structure with discontinuous geopolymer gel phases, which contributed to the high water absorption capacity of the control mix.

The addition of silica fume to the geopolymer mixes (M1 and M4) significantly reduced the water absorption capacity from 5.2% to 5.0%. This can be associated with the very small particle size and high amorphous silica content of silica fume, which are beneficial for pore filling and geopolymer gel continuity. SEM micrographs of the mixes indicated a pore structure with reduced pore size and limited interconnectivity, which restricted water penetration into the geopolymer matrix.

The mixes containing fly ash alone, that is, mixes M2 and M5, were observed to exhibit reduced water absorption, with values ranging from 5.8 to 6.1%. From the SEM results, partially reacted spherical fly ash particles were observed to be present within the geopolymer matrix, indicating secondary geopolymerization reactions that continue to improve the pore structure of the geopolymer concrete. The presence of partially interconnected pores at the age of the test may be the limiting factor in the extent of water absorption reduction observed in the mixes. The blended mixes containing fly ash and silica fume, that is, mixes M3 and M6, exhibited the lowest water absorption values, with a minimum value of 4.3% observed for mix M6. The reduced water absorption observed in the blended mixes indicates the synergistic effect of the refinement of the pores in the geopolymer concrete, with the silica fume contributing to the refinement of the pores during the early stages of geopolymerization and the fly ash continuing the geopolymerization reaction to result in the closure of the capillary pores. The dense and homogeneous microstructure of the geopolymer concrete disrupted the continuity of the water flow, resulting in an observed improvement in the durability of the geopolymer concrete.

3.5 Correlation between scanning electron microscopy observations and mechanical properties

Figures 1-7 depict the SEM micrographs of the metakaolin geopolymer concrete mixes, namely, M0, M1, M2, M3, M4, M5, and M6, indicating the microstructural development of the geopolymer concrete mixes with increased percentages of fly ash and silica fume additions. Mix M0, as presented in Figure 1, showed a porous and heterogeneous microstructure, comprising unreacted metakaolin plate-like particles and a discontinuous N-A-S-H geopolymer gel matrix. This led to the development of comparatively low compressive and tensile strengths in the control mix. As indicated by the SEM micrographs of mixes M1 and M2, presented in Figure 2 and 3, respectively, the geopolymerization reaction between the fly ash particles and the alkaline solution was in progress, resulting in the formation of a geopolymer gel around the partially reacted fly ash particles. This resulted in improved interparticle bonding in the geopolymer matrix. However, the presence of a significant percentage of unreacted fly ash particles and pores restricted the development of increased strength in the mixes.

Significant microstructural development was observed for the silica fume-containing mixes, particularly mix M3, as shown in Figure 4. This resulted from the presence of ultrafine silica fume particles, which ensured pore filling and the formation of a geopolymer gel matrix.

The hybrid mix M4 in Figure 5 shows a highly compact microstructure with a thick and continuous coating of N–A–S–H gel. The synergistic effect of fly ash and silica fume is responsible for the absence of interconnected voids and the improved efficiency of stress transfer.

The continuity of the geopolymer gel and the closure of microvoids are also evident in mix M5, as shown in Figure 6. The thickness of the geopolymer gel and the presence of closed microvoids are indicative of an advanced microstructure. This resulted in improved water absorption and impermeability of the mix. The most compact and homogeneous microstructure is observed for mix M6, as shown in Figure 7. The matrix was almost free of pores, and the geopolymer gel was highly continuous. This indicates an advanced degree of geopolymerization. This microstructure is responsible for the improved mechanical properties and durability of mix M6.

The SEM results thus confirmed that the mechanical properties and durability performance of geopolymer concrete are strongly influenced by microstructural factors. The progressive improvement in the performance of each mix from M0 to M6 is thus attributed to the synergistic effect of fly ash and silica fume on the development of the geopolymer gel.

3.6 Overall discussion

A combined analysis of the compressive strength, splitting tensile strength, flexural strength, and water absorption revealed that the incorporation of fly ash and silica fume drastically enhanced the MGC performance. Fly ash adds to the long-term strength and durability of concrete, whereas silica fume contributes to early strength and improvement in the microstructure. These SCMs had a synergetic effect, leading to the acquisition of superior mechanical and durability properties compared to the MGC prepared with only metakaolin addition. Therefore, MGC mixed with fly ash and silica fume is a promising sustainable high-performance alternative to traditional Portland cement concrete for various structural purposes related to durability and strength.

3.7 Variance analysis

One-way ANOVA was conducted to statistically confirm the differences in the mechanical performance of the geopolymer concrete (M0-M6). A summary of the findings of the analysis is presented in Table 3. Three tests were performed at a 95% confidence level.

The F-value (15.62) of the compressive strength was statistically significant with a p-value (0.0023) and was much greater than the critical F0 (2.84), implying that there was a statistically significant difference between the mixes. The results of the splitting tensile strength test also proved that differences were not obtained because of the effect of random errors: F = 9.47, F ncritical n = 2.84, and p = 0.0061. There was also an appreciable variation in the flexural strength outcome: F = 12.83, F northern critical n = 2.84, and P = 0.0038.

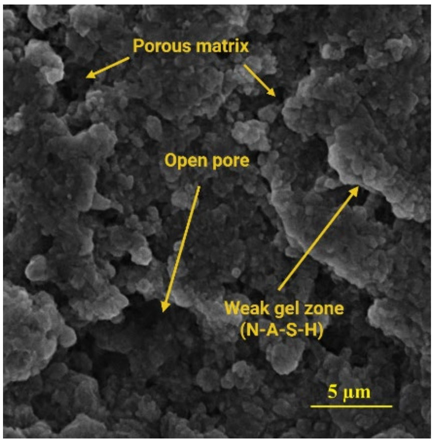

Figure 1. Scanning electron microscopy of mix M0 showing porous geopolymer matrix

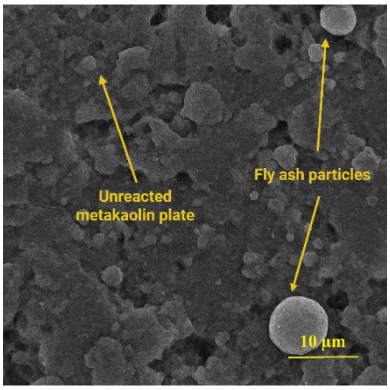

Figure 2. Scanning electron microscopy of mix M1 showing matrix densification with silica fume

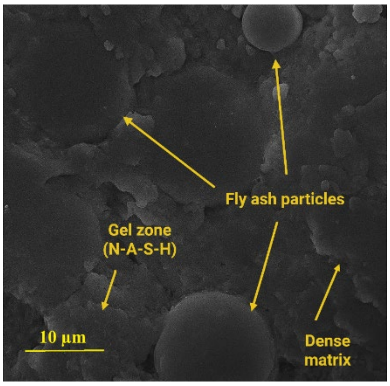

Figure 3. Scanning electron microscopy of mix M2 showing partially reacted fly ash particles

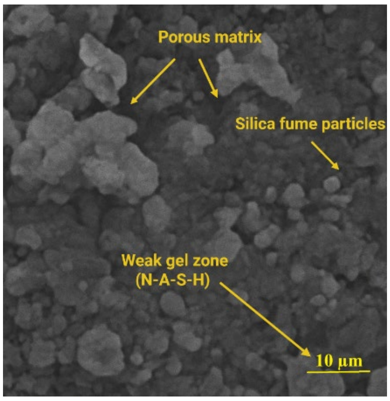

Figure 4. Scanning electron microscopy of mix M3 showing refined pore structure

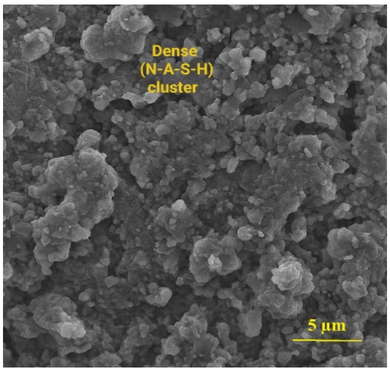

Figure 5. Scanning electron microscopy of mix M4 showing dense hybrid gel matrix

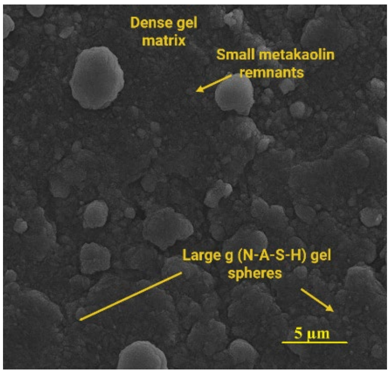

Figure 6. Scanning electron microscopy of mix M5 showing increased gel continuity

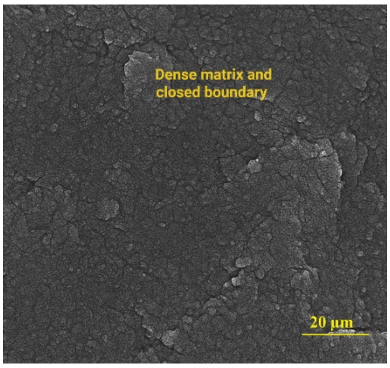

Figure 7. Scanning electron microscopy of mix M6 showing compact geopolymer matrix

Table 3. One-way analysis of variance (ANOVA) results for mechanical and durability properties of metakaolin-based geopolymer concrete (MGC) mixes

Property	Mix Range	F-Value	F-Critical	p-Value	SD / CV
Compressive Strength	M0–M6	15.62	2.84	0.0023	0.41–1.06 / 4.8–2.1%
Splitting Strength	M0–M6	9.47	2.84	0.0061	0.23–0.58 / 5.2–2.5%
Flexural Strength	M0–M6	12.83	2.84	0.0038	0.31–0.69 / 4.5–2.2%
Water Absorption	M0–M6	10.21	2.84	0.0049	0.12–0.33 / 6.1–2.7%

The geopolymerization process became more consistent and homogeneous with the increase in percentages of fly ash and silica fume as the coefficients of variation (CV) in M0 decreased to 2.1% in M6, and the standard deviations (SD) in the compressive strength results becoming 0.41 to 1.06 MPa.

Therefore, the ANOVA results demonstrated that the incorporation of fly ash and silica fume had a significant effect on the mechanical properties of the geopolymer concrete and rejected the null hypothesis. As per the microstructural densification and strengthening of the geopolymer matrix bond, the mixed blends (M4M6) demonstrated statistically better performance.

4. CONCLUSION

This study established that the mechanical performance and durability of MGC were significantly enhanced from 32.5 MPa to 44.2 MPa by the concomitant addition of fly ash (FA) and silica fume (SF). Compared to the reference mix, the favourable mixture (M6) showed great enhancement in compressive, splitting tensile, and flexural strengths and a considerable reduction in water uptake, indicating a denser and less permeable microstructure. The hybrid binder system exhibited a synergistic effect.

When reactive silica in SF and aluminosilicates in FA were combined simultaneously, a more uniform and compact geopolymer network using well-developed N-A-S-H gel and efficient pore filling was obtained. This leads to improved load transfer, resistance to cracks, and durability. Statistical analysis of the results of the one-way ANOVA shows that these performance gains are statistically significant and do not occur as a result of random variation. Greater material homogeneity and reproducibility were reflected in the smaller spread in the results of the hybrid mixes.

With respect to sustainability, the ternary binder system that has been proposed (MK-FA-SF) offers an advanced and more environmentally friendly option than traditional PC concrete. The partial substitution of metakaolin with industrial waste products, namely fly ash and silica fume, results in a ternary system having a more sustainable footprint than OPC-based binders, mainly in terms of the reduced consumption of clinker and waste valorization.

Overall, the experimental results demonstrate that the combined use of fly ash and silica fume results in superior mechanical and durability properties compared with the individual use of these waste products, offering an opportunity for the development of more sustainable geopolymer binders.

5. LIMITATIONS AND FUTURE WORK

Although the present study offers considerable insight into the synergistic potential of FA and SF in the context of MKA-based geopolymer concrete systems, some limitations of the study need to be recognized. First, the experimental study was conducted only at a particular curing age, that is, 28 days. However, the long-term characteristics of the concrete system, such as the evolution of strength, shrinkage, and durability under adverse environmental conditions, were not addressed in the study. Second, the study was conducted only at the laboratory scale under controlled conditions, which may not be a true representation of the characteristics associated with the production of concrete at a larger scale.

Therefore, further studies are required to evaluate the long-term characteristics of the proposed concrete system in the context of strength, durability, and resistance to adverse environmental conditions. Moreover, the workability and setting characteristics of the concrete system must be evaluated to assess the practical potential of ternary geopolymer concrete systems. Furthermore, a life-cycle assessment (LCA) study can be conducted to evaluate the environmental advantages of the proposed concrete system in comparison with the conventional concrete system based on the use of OPC.

ACKNOWLEDGMENTS

The authors sincerely thank Mustansiriyah University for the facilities and ongoing support they received while conducting this study.

REFERENCES

[1] Abdulhussein, S.S., Jaafar, E. K., Fawzi, N.M. (2024). Impact of temperatures on the mechanical characteristics of modified reactive powder concrete. AIP Conference Proceedings, 3229(1): 030004. https://doi.org/10.1063/5.0236203.

[2] Ghadban, R., Kamil, L., Abdulhussein, S., Abdulrehman, M., Flayyih, A. (2026). Sustainable translucent geopolymer concrete based on metakaolin and recycled glass. AIMS Materials Science, 13(1): 80. https://doi.org/10.3934/matersci.2026005

[3] Barbhuiya, S., Das, B.B., Adak, D. (2025). Data-driven approaches in concrete science: Applications, challenges and future prospects. In Proceedings of the Institution of Civil Engineers-Construction Materials, pp. 1-17. https://doi.org/10.1680/jcoma.24.00018

[4] Abdulhussein, S.S., Johari, I., Fawzi, N.M. (2025). Mechanical properties of sustainable structural aerated-polystyrene concrete. World Journal of Engineering, 22(5): 1018-1028. https://doi.org/10.1108/WJE-01-2024-0047.

[5] Provis, J.L., van Deventer, J.S.J. (2014). Alkali-activated materials: State-of-the-art report. RILEM State-of-the-Art Reports, Springer, Dordrecht. https://doi.org/10.1007/978-94-007-7672-2

[6] Bernal, S.A., Provis, J.L., Walkley, B., San Nicolas, R., Gehman, J.D., Brice, D.G., Kilcullen, A.R., Duxson, P.,

van Deventer, J.S.J. (2013). Gel nanostructure in alkali-activated binders based on slag and fly ash. Cement and Concrete Research, 53: 127-144. https://doi.org/10.1016/j.cemconres.2013.06.007
[7] Salman, A.A., Abdulrehman, M.A., Mohammed, A.H., Goaiz, H.A. (2026). When nanoparticles hurt: A critical assessment of SiO_2 and Al_2O_3 in Cement Mortar. Results in Materials, 29: 100887. https://doi.org/10.1016/j.rinma.2026.100887
[8] Sindhurashmi, B.M., Nayak, G., Adesh, N.D., Rao, V., Dubey, S.P. (2024). Incorporating sea sand into self-compacting concrete: A systematic review. Discover Applied Sciences, 6(4): 194. https://doi.org/10.1007/s42452-024-05826-0
[9] Khair, S., Rahman, S.A., Shaikh, F.U.A., Sarker, P.K. (2024). Evaluating lithium slag for geopolymer concrete: A review of its properties and sustainable construction applications. Case Studies in Construction Materials, 20: e02822. https://doi.org/10.1016/j.cscm.2023.e02822
[10] Adelfio, L. (2025). From Laboratory to Industry: Feasibility Assessment of Industrial Production of Waste-Based Geopolymers. https://core.ac.uk/download/656719119.pdf.
[11] Verma, P., Goldar, D., Singh, S.K., Daniyal, M. (2024). Performance evaluation and enhancement of geopolymer concrete using silica fume. International Journal of Civil Engineering, 11(11): 78-88. https://doi.org/10.14445/23488352/ijce-v11i11p108
[12] Bernal, S.A., Rodríguez, E.D., Kirchheim, A.P., Provis, J.L. (2016). Management and valorisation of wastes through use in producing alkali-activated cement materials. Journal of Chemical Technology & Biotechnology, 91(9): 2365-2388. https://doi.org/10.1002/jctb.4927
[13] Zhang, Z., Provis, J.L., Reid, A., Wang, H. (2014). Geopolymer foam concrete: An emerging material for sustainable construction. Construction and Building Materials, 56: 113-127. https://doi.org/10.1016/j.conbuildmat.2014.01.081
[14] Luhar, S., Nicolaides, D., Luhar, I. (2021). Fire resistance behaviour of geopolymer concrete: An overview. Buildings, 11(3): 82. https://doi.org/10.3390/buildings11030082
[15] Yang, M., Chen, L., Lai, J., Osman, A.I., Farghali, M., Rooney, D.W., Yap, P.S. (2024). Advancing environmental sustainability in construction through innovative low-carbon, high-performance cement-based composites: A review. Materials Today Sustainability, 26: 100712. https://doi.org/10.1016/j.mtsust.2024.100712
[16] Wang, P., Ma, M., Wang, F. (2025). Research hotspots and frontiers in metakaolin-based geopolymer studies: A bibliometric analysis. Discover Applied Sciences, 7(2): 87. https://doi.org/10.1007/s42452-025-06496-2
[17] Penazzato, L., Illampas, R., Oliveira, D.V. (2024). The challenge of integrating seismic and energy retrofitting of buildings: An opportunity for sustainable materials? Sustainability, 16(8): 3465. https://doi.org/10.3390/su16083465
[18] Mohamed, O., Zuaiter, H. (2024). Fresh properties, strength, and durability of fiber-reinforced geopolymer and conventional concrete: A review. Polymers, 16(1): 141. https://doi.org/10.3390/polym16010141
[19] Zaid, O., Sor, N.A.H., Martínez-García, R., de Prado-Gil, J., Elhadi, K.M., Yosri, A.M. (2024). Sustainability evaluation, engineering properties and challenges relevant to geopolymer concrete modified with different nanomaterials: A systematic review. Ain Shams Engineering Journal, 15(2): 102373. https://doi.org/10.1016/j.asej.2023.102373
[20] Ahmed, H.U., Mohammed, A.A., Mohammed, A. (2022). Soft computing models to predict the compressive strength of GGBS/FA-geopolymer concrete. PLoS One, 17(5): e0265846. https://doi.org/10.1371/journal.pone.0265846
[21] BS EN 12390-3. (2009). Testing Hardened Concrete—Part 3: Compressive Strength of Test Specimens. Management Centre: Avenue Marnix 17, B-1000 Brussels.
[22] ASTM International. (2017). ASTM C496/C496M-17: Standard test method for splitting tensile strength of cylindrical concrete specimens. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/C0496_C0496M-17
[23] ASTM International. (2018). ASTM C78/C78M-18: Standard test method for flexural strength of concrete (using simple beam with third-point loading). ASTM International, West Conshohocken, PA. https://doi.org/10.1520/C0078_C0078M-18
[24] Abdulhussein, S.S., Johari, I.B., Fawzi, N.M. (2024). Mechanical properties of aerated-polystyrene concrete reinforced by polymer fibers. Annales de Chimie - Science des Matériaux, 48(4): 435-445. https://doi.org/10.18280/acsm.480401
[25] ASTM International. (2021). ASTM C642-21: Standard test method for density, absorption, and voids in hardened concrete. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/C0642-21