Physical and Mechanical Properties of Fly Ash-Based Geopolymer Mortar With a Combination of Metakaolin and Silica Fume

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Abstract. The construction sector's significant contribution to global carbon emissions, particularly through Portland cement manufacturing, has intensified the need for sustainable material solutions. This research investigates the performance characteristics of fly ash-based geopolymer mortar as an eco-friendly cementitious alternative, focusing on optimizing its properties through supplementary aluminosilicate materials. The experimental program evaluates four distinct mix designs of geopolymer and one variation of conventional as a control: (1) MK (Conventional), (2) MGFA (pure fly ash), (3) MGFS (50% fly ash/50% silica fume), (4) MGFM (50% fly ash/50% metakaolin), and (5) MGFMS (50% fly ash/25% metakaolin/25% silica fume). All formulations of geopolymers utilize a 12M molarity with a 20% water content enhancement to assess workability and reaction kinetics. The study analyzed the density and compressive strength of mortar. The best mixture of geopolymer was (MGFMS), which reached a compressive strength of 23.04 MPa due to forming strong Si-O-Al bonds that create a solid framework. However, this strength is still lower than that of conventional mortar, which reaches 32.41 MPa. In contrast, the mixture of (MGFM) showed the lowest strength which is 12.56 MPa, attributed to high porosity from the metakaolin geopolymerization process. These results indicate that geopolymer mortar holds significant potential as a sustainable alternative. However, further adjustments in material ratios and activators are necessary to improve its performance in future applications.

Introduction

In the construction industry, concrete and mortar are the most common building materials made from main components like coarse aggregates, fine aggregates, water, and Portland cement. These materials are frequently used in infrastructure projects because they are relatively inexpensive, easy to obtain, have high compressive strength, are simple to shape as per design, and generally require little special care when used for structural components. However, as infrastructure development increases, the demand for cement production will also grow [1].

Considering future development problems that use cement as the primary material in concrete or mortar, the production of Portland cement as a construction material needs to be reduced, given that cement has a considerable carbon footprint. According to the USGS, the total cement production worldwide has reached 4.1 billion tons annually in recent years. Based on data from the Chatham House research institute, it is estimated that the cement industry accounts for about 8% of total global anthropogenic CO_2 emissions, which means approximately 325 million tons of CO_2 are released into the atmosphere each year, making cement the second-largest producer of greenhouse gases [2]. Another consideration is the availability of the primary sources of environmentally friendly concrete and mortar components, which are much more abundant on Earth (silica 27.7% and alumina 8.1%) compared to the primary source of Portland cement (calcium 3.6%) [3].

The construction industry's environmental impact necessitates transitioning from conventional Portland cement to more ecologically responsible binding systems. Geopolymer technology presents a viable solution, utilizing aluminosilicate precursors activated through alkaline solutions to create sustainable cementitious composites. This approach fundamentally differs from conventional cement production by employing industrial byproducts as primary raw materials while eliminating the need for high-temperature clinker processing [4]. One of the most widely available and commonly used sources of alumina silica is fly ash, which totaled 8.31 million tons annually in 2019. According to the K3 expert of the Jeranjang Steam Power Plant, this component is typically found in industrial by-products, such as fly ash in this study. This material results from coal combustion at the Jeranjang Steam Power Plant, which produces 30,000 tons per year. Most of this material is disposed of, causing environmental damage to soil, water, and air.

In geopolymer studies, challenges include strength, porosity, and workability during manufacturing, so an additional material is needed to address these issues. In one of the previous studies that used fly ash as a cement substitute, it was stated that class F (low-CaO) fly ash requires thermal curing (60-80°C) to achieve optimal strength because of its low aluminosilicate reactivity at ambient temperature [5]. So, applying fly ash at ambient temperature requires an extra material to help it reach optimal levels of performance. One such material is silica fume, which contains minerals rich in silica (Si), a pozzolanic substance resistant to sulfates and chlorides. Silica fume is used because its excellent particles fill pore gaps in the mixture, making it denser by reducing pore size and overall pore volume. Additionally, metakaolin, a clay mineral increasingly used in concrete, has highly reactive properties, is environmentally friendly, widely available, and contains significant amounts of silica (Si) and alumina (Al). Its use can improve concrete quality. When these materials are combined to form a geopolymer mortar that matches or exceeds the strength of traditional mortar, it can reduce Portland cement production and increase the use of fly ash. Ultimately, this helps lower carbon dioxide (CO_2) emissions from cement manufacture and addresses waste disposal concerns for fly ash, silica fume, and metakaolin.

In light of the challenges as mentioned above, this study systematically examines the influence of metakaolin and silica fume supplementary cementitious materials on the performance characteristics of fly ash-based geopolymer mortar under ambient curing conditions. The investigation focuses on quantifying the enhancement of both physical and mechanical properties, while assessing the material's viability for industrial-scale implementation.

Theoretical Basis

As sustainable construction materials, geopolymers depend on alkali polymerization reactions between aluminosilicate sources (such as fly ash) and alkaline activators (NaOH/KOH) to form three-dimensional structures similar to Portland cement, but with significantly lower CO_2 emissions [4]. Fly ash, a byproduct of coal-fired power plants, has become a primary raw material because of its abundant availability and high SiO_2-Al_2O_3 content [6]. However, previous studies have identified fundamental limitations, especially the variability in the chemical composition of fly ash, which impacts the consistency of geopolymerization reactions [7]. Furthermore, Class F fly ash (low calcium) often shows low reactivity at ambient temperatures, requiring modification with supplementary materials such as metakaolin or silica fume [8].

Previous research on fly ash-based geopolymer mortar has identified several key limitations that prevent its wider use. A significant issue is the low reactivity of fly ash under normal curing conditions, requiring thermal curing to gain sufficient mechanical strength. However, this demand is often impractical for in-situ construction, especially in areas with limited infrastructure. Furthermore, the different chemical compositions of fly ash from various sources cause inconsistent performance of geopolymer mortar [7]. This study proposes combining fly ash with metakaolin and silica fume to address these issues. Metakaolin, containing substantial Al_2O_3 content and high reactivity, can accelerate geopolymer gel formation. Meanwhile, silica fume contributes to matrix densification through filler effects and secondary C-S-H gel formation [9][10]. Optimizing the ratio of these three materials is expected to yield mortar that reaches optimal strength under ambient curing conditions, thereby improving its practical use in field applications.

Moreover, the workability issues of fly ash-based materials demand significant development. Studies show that while a higher calcium content in fly ash boosts geopolymer compressive strength, it also causes faster setting times that significantly reduce the workability of concrete or mortar. Therefore, the characteristics of geopolymer concrete or mortar-including setting time and compressive strength are heavily affected by fly ash characteristics, including physical traits, pH level, and chemical makeup.

Considering these challenges from previous studies, the fly ash-metakaolin-silica fume geopolymer mortar is expected to become a sustainable solution with high performance, excellent durability, and easy application. Future deployment of this research could include a life cycle assessment (LCA) to verify its environmental benefits over conventional materials, further supporting its adoption in green construction industries.

Methods

Research Method. This study employs an experimental approach to evaluate the effects of metakaolin and silica fume additives on the performance characteristics of fly ash-based geopolymer mortar under ambient curing conditions. The investigation utilizes standardized cubic specimens with dimensions of 50 mm × 50 mm × 50 mm as shown in **Fig. 1**, to assess key material properties, including density and compressive strength. Compressive strength measurements are obtained at the 28-day curing interval using a Universal Testing Machine (UTM) following the standard of ASTM C109 [11], as shown in **Fig. 2**.

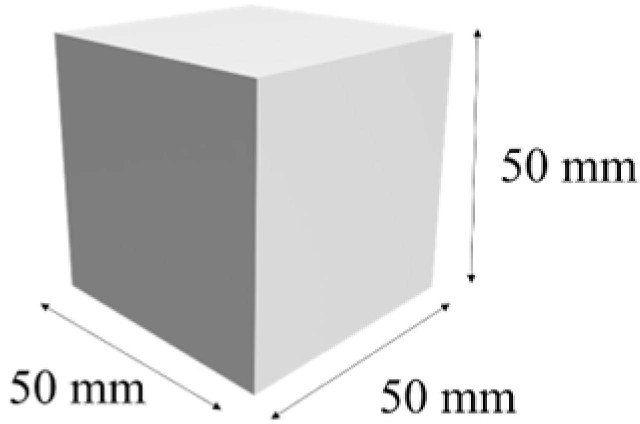

Fig. 1. Test Specimen

Fig. 2. Compressive Strength Test

Specimen Preparation and Curing. The geopolymer mortar mixtures were poured into 50 mm × 50 mm × 50 mm wooden molds in two separate layers. Each layer was compacted with a tamping rod using 32 strokes for proper densification. After casting, the specimens were demolded after 24 hours at room temperature. This study employed ambient curing as the primary method, maintaining the specimens at controlled environmental conditions (25 ± 2°C, 95% relative humidity) until the 28-day testing age was reached. The ambient curing approach was specifically selected based on practical considerations regarding room-temperature performance, aligning with the research objective of developing field-applicable geopolymer materials.

Mix Design Specimens. This research used four variations of geopolymer mortar mixtures, as shown in **Table 1**, regarding the Mix Design Proportion. One conventional mortar was used as a control to compare the performance of the planned geopolymer variation, as follows:

Table 1. Mix Design Proportion

Variation	**Sand**	**FA**	**MK**	**SF**	**Activator**	**SP**	**Extra water**	**Cement**
	(gr)	**(gr)**	**(gr)**	**(gr)**	**(ml)**	**(ml)**	**(ml)**	**(gr)**
MK	150	-	-	-	-	-	75	150
MGFA	150	150	-	-	60	2.25	30	-
MGFM	150	75	75	-	60	2.25	30	-
MGFMS	150	75	37.5	37.5	60	2.25	30	-
MGFS	150	75	-	75	60	2.25	30	-

This mixed design was systematically developed to evaluate the effects of aluminosilicate material combinations on geopolymer mortar performance. The MGFA composition is the baseline control for assessing conventional material performance, while MGFM variation was incorporated to enhance reactivity through metakaolin's high Al_2O_3 content, which accelerates geopolymer gel formation. The MGFS formulation utilizes silica fume particles as filler material and a reactive silica source to improve matrix density. The MGFMS mixture was designed to create the bond between aluminum-rich metakaolin and silica-rich fume, potentially achieving the optimal Si/Al ratio for peak performance. A consistent 50% fly ash proportion was maintained to preserve the environmental benefits of this sustainable material. At the same time, the 0.4 activator ratio and 12M of molarity were chosen based on preliminary studies demonstrating optimal workability and performance within this range. These variations enable comprehensive analysis of each additive's impact on the mortar's physical and mechanical properties.

Results and Discussion

XRF (X-Ray Fluorescence) Test. The XRF test revealed the chemical composition of the fly ash utilized in this investigation, demonstrating a calcium oxide (CaO) content of 13.7% by mass. Furthermore, the combined percentage of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3) was quantified at 68.5%. Based on the ASTM C618-03 standard, these compositional characteristics confirm the material's classification as Class F fly ash, meeting the dual criteria of containing less than 18% CaO while maintaining a combined SiO_2+Al_2O_3+Fe_2O_3 content exceeding the 50% threshold [12].

Density. The data presented in **Fig. 3**, shows that the conventional mortar specimen achieved a peak density value of 2.013 g/cm³. This elevated density can be attributed to the material properties of Portland cement, particularly its characteristically high specific gravity and compact microstructure. The composition (MGFS) demonstrated the optimal density at 1.819 grams/cm³ among the geopolymer mortars tested. This decrease in density is probably caused by silica fume, which, despite reducing overall density, can enhance strength by filling voids in the mixture. Silica fume particles are excellent at filling cavities, thereby lowering the density. Conversely, the (MGFM) variation recorded the lowest density at 1.774 grams/cm^3. This suggests that, although metakaolin boosts the reactivity of geopolymers, it also promotes pore formation in the mixture, which can decrease the mortar's overall density.

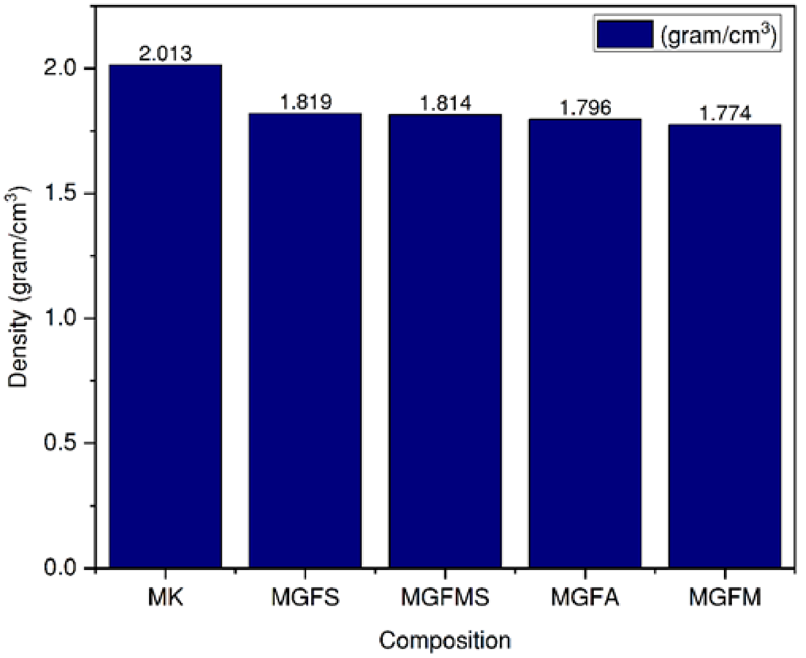

Fig. 3. Density measurement results for mortar specimens

Compressive Strength of Mortar. As illustrated in **Fig. 4**, conventional Portland cement mortar demonstrates the highest compressive strength relative to all geopolymer formulations examined. This enhanced mechanical performance stems from the material's densely packed matrix structure and the well-developed calcium silicate hydrate (C-S-H) bonding network [5], so the porosity is lower compared to other geopolymer variations. Conversely, the geopolymer (MGFM) exhibits the lowest compressive strength, primarily due to high porosity from water release during the metakaolin geopolymerization process. This may also result from a suboptimal activator ratio, which might not fully activate all the aluminosilicate materials, coupled with the clustering of fine metakaolin and fly ash particles, reducing the overall density of the specimen.

The graph in **Fig. 5** indicates that the composition (MGFMS) has the highest performance among geopolymer options. As illustrated, blending reactive metakaolin with silica fume as a cavity filler helps balance reactivity and density. The silica fume fills pores thanks to the metakaolin, which can enhance the mortar's compressive strength [8].

Fig. 4. Compressive Strength Testing of Mortar Samples

Examining the graph of the mortar's compressive strength in **Fig. 5** and comparing it with the density graph in **Fig. 3** reveals that surface weight does not always correlate linearly with compressive strength. This inconsistency is evident in the variations seen with different compositions, such as MGFMS variation. The observed inconsistency between density and compressive strength parameters may originate from heterogeneous aggregate distribution within the chemical bonds. At the same time, such non-uniform dispersion can elevate bulk density measurements, but it fails to improve the strength of geopolymeric bonding networks. This phenomenon ultimately manifests as reduced compressive capacity despite apparent densification [13]. The observed non-proportional relationship between density and compressive strength parameters can be attributed to non-optimal activator-to-precursor ratios in the geopolymer formulation. This suboptimal chemical bond leads to inadequate interfacial bonding between the aluminosilicate binder and aggregate particles and microstructural irregularities that influence both the effective load-bearing surface area and stress distribution characteristics during compressive loading. These factors affect the volume's weight but do not primarily lead to an increase or decrease in its compressive strength [14].

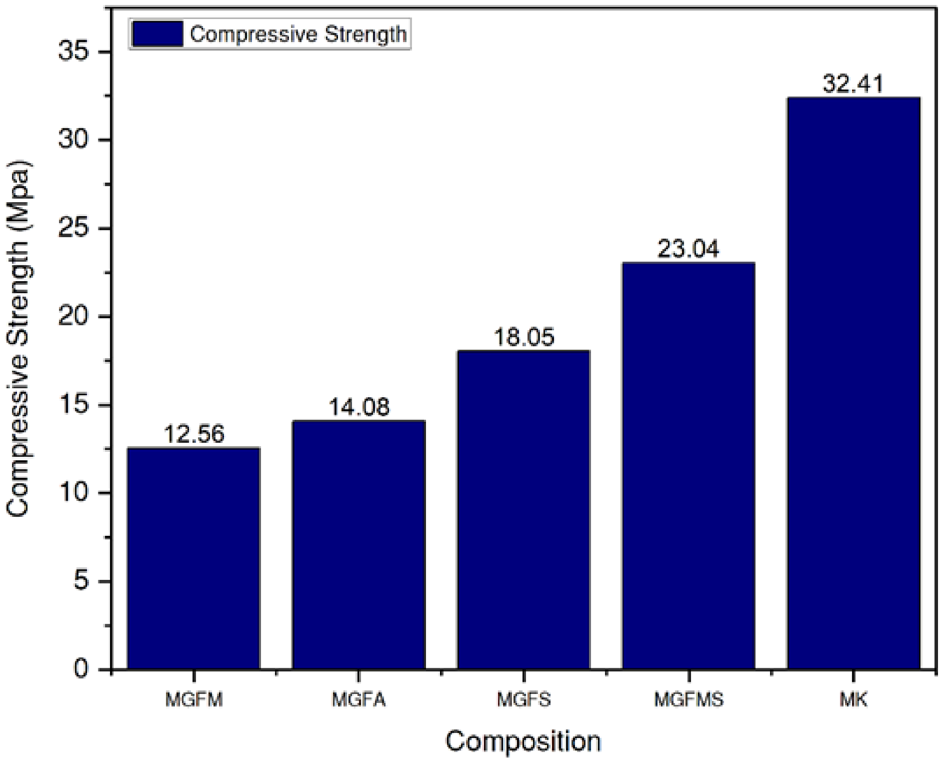

Fig. 5. Graph the results of the compressive strength test

The compressive strength results obtained in this study align with the initial hypothesis, which suggested that the mortar could reach at least 15 MPa for structural use. In the latest geopolymer study, previous researchers who used the combination of fly ash and silica fume had similar results in this study, achieving a compressive strength value of 22.1 MPa [15], and 25.7 MPa [16], this may be due to the relatively small substitution of silica fume for fly ash, which reduces the prominence of silica fume's role. Therefore, further optimization of the silica fume substitution percentage is necessary. Meanwhile, the previous researcher used a combination of fly ash and metakaolin, achieving the highest compressive strength of 44.2 MPa [15], this can be caused by the optimal ratio of solution and material proportions and supported by the curing method employed, specifically high-temperature curing, which can accelerate the geopolymerization process and improve the mechanical performance of geopolymers.

Previous studies on this combination show results that differ significantly from this study, highlighting the need for further material optimization. While still distinct from the comparison, this research offers new perspectives on developing geopolymer materials. The current results require additional refinement, particularly concerning material proportions and solution ratios, which should be optimized to improve the mixture's performance and practicality. Such improvements could facilitate scaling up the application, including use in structural concrete applications.

Summary

Based on the results and analysis conducted, here are some key summaries that can be drawn from this study:

1. The variation of the geopolymer with code (MGFMS) shows the highest value, which is 23.04 MPa. This indicates that combining metakaolin and silica fume can form strong geopolymer bonds, thereby enhancing the mortar's performance. In contrast, the variation with the code (MGFM) has the lowest compressive strength of 12.56 MPa. This suggests that excessive substitution of metakaolin without additives like silica fume can increase porosity, which weakens the material mixture.
2. It is important to make NaOH solutions, alkaline activators, and mix materials carefully because an error resulting from a lack of control in the mixing process can affect the mixture produced.
3. This study's achievements still need further improvement, especially in the material proportions and the solution ratio, which should be optimized to achieve better and more practical mixture performance, enabling development on a larger scale, such as in structural concrete applications.

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