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Optimization of Geopolymer Mortar Performance Using Locally Sourced Precursors: An Experimental and Statistical Approach

Tryandi Adi Muhlis [1]✉, Jauhar Fajrin [2], Ni Nyoman Kencanawati [3]
(1,2,3) Department of Civil Engineering, Mataram University, Mataram, Indonesia

Abstract: *Fly ash-based geopolymer mortar is a promising alternative to Portland cement because it utilizes aluminosilicate-rich industrial by-products and reduces cement consumption. This study investigated metakaolin, calcined clay, and rice husk ash as supplementary precursors and four $NaOH/Na_2SiO_3$ ratios (1:1.5, 1:2, 1:2.5, and 1:3) on the density, water absorption, and compressive strength of fly ash-based geopolymer mortar. A full factorial experimental design (3 × 4) was employed, with five specimens for density and compressive strength testing and three specimens for water absorption testing. Raw materials were characterized using X-ray fluorescence, and mortar properties were evaluated at 28 days. The data were analyzed using Two-Way Analysis of Variance at a 5% significance level, preceded by the Anderson–Darling normality test. Tukey's Honestly Significant Difference test was applied to significant main effects. The results showed that supplementary precursor type and $NaOH/Na_2SiO_3$ ratio significantly affected compressive strength and water absorption ($p < 0.05$), whereas neither factor significantly affected density. No significant interaction was observed between the two factors for any evaluated property. The highest observed compressive strength was obtained by the metakaolin mixture at a $NaOH/Na_2SiO_3$ ratio of 1:2.5, reaching 18.01 MPa. Although the calcined clay mixture at the same ratio exhibited the highest observed density (2.22 g/cm^3), density was not significantly affected by either factor. These findings demonstrate that precursor type and alkaline activator ratio significantly influence compressive strength and water absorption, while their effects on density and interaction are not statistically significant.*

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INTRODUCTION

The construction industry is one of the largest contributors to global carbon dioxide (CO_2) emissions because of the extensive use of Portland cement as the primary binder in concrete and mortar. Cement production is estimated to account for approximately 7–8% of global anthropogenic CO_2 emissions, highlighting the urgent need for low-carbon construction materials (Lehne & Preston, 2018). Among the available alternatives, fly ash-based geopolymer has attracted considerable attention because it utilizes aluminosilicate-rich industrial by-products while significantly reducing the dependence on Portland cement (Davidovits, 2020).

Fly ash is one of the most widely used geopolymer precursors due to its high silica (SiO_2) and alumina (Al_2O_3) contents, which react with alkaline activators to form sodium aluminosilicate hydrate (N-A-S-H) gel as the primary binding phase. As a result, fly ash-based geopolymer mortar exhibits satisfactory mechanical strength, excellent chemical resistance, and good thermal stability, making it a promising alternative to conventional cementitious mortar (Aouan et al., 2021; Zhu et al., 2019).

✉ *Corresponding author:* ***tryandi26m@gmail.com***

However, variations in the chemical composition and reactivity of fly ash from different sources often result in inconsistent geopolymer properties.

To improve geopolymer performance, numerous studies have incorporated supplementary precursors rich in reactive aluminosilicates. Metakaolin has been widely reported to enhance compressive strength because of its high reactivity (Albidah et al., 2021; Archer de Carvalho et al., 2024; Harmaji et al., 2023), whereas calcined clay and rice husk ash contribute to matrix densification and microstructural refinement through additional reactive silica and alumina (Athira & Sathyan, 2026; Boakye & Khorami, 2023; Mulapeer & Omar, 2025). Previous studies have also demonstrated that the type and proportion of supplementary precursor substantially influence the physical and mechanical properties of geopolymer mortar (Logesh Kumar & Revathi, 2016; Nana et al., 2021; Zahid et al., 2017).

Besides precursor characteristics, the composition of the alkaline activator plays an equally important role in geopolymerization. The $NaOH/Na_2SiO_3$ ratio governs the dissolution of aluminosilicate species, gel formation, and the development of the geopolymer matrix. Several studies have shown that an appropriate activator ratio improves compressive strength and reduces pore connectivity, whereas excessively low or high ratios may adversely affect geopolymer performance (Albidah et al., 2021; Aouan et al., 2021; Hadi et al., 2018; Karyawan et al., 2022).

Although many studies have investigated either supplementary precursor type or alkaline activator ratio, relatively few have evaluated both factors simultaneously using a factorial experimental design. Furthermore, previous studies have generally relied on descriptive comparisons without statistically verifying the independent effects of each factor. Inferential statistical analysis, particularly Two-Way Analysis of Variance (Two-Way ANOVA), provides a robust approach for determining whether the observed differences are attributable to precursor type, activator ratio, or their interaction (Montgomery, 2019). This statistical approach therefore provides an opportunity to evaluate the two factors simultaneously under controlled experimental conditions. The novelty of this study lies in the simultaneous evaluation of three locally available supplementary precursors and four $NaOH/Na_2SiO_3$ ratios within a full-factorial experimental design. This approach enables the individual effects of precursor type and activator ratio, as well as their interaction, to be statistically evaluated under consistent mixture proportions and curing conditions.

Therefore, this study investigates the effects of three locally available supplementary precursors, namely metakaolin, calcined clay, and rice husk ash, and four $NaOH/Na_2SiO_3$ ratios (1:1.5, 1:2, 1:2.5, and 1:3) on the density, water absorption, and compressive strength of fly ash-based geopolymer mortar. In addition, Two-Way ANOVA was employed to evaluate the statistical significance of precursor type, activator ratio, and their interaction. The findings provide statistically validated evidence for identifying the best-performing combinations of supplementary precursor and alkaline activator ratio under the investigated conditions.

RESEARCH METHOD

Research Design

This study employed a quantitative experimental approach to investigate the effects of supplementary precursor type and alkaline activator ratio on the physical and mechanical properties of fly ash-based geopolymer mortar. Two independent factors were investigated: (1) supplementary precursor type, consisting of metakaolin (MK), calcined clay (CL), and rice husk ash (RHA), and (2) alkaline activator ratio, consisting of four levels. A full factorial experimental design with three supplementary precursor types and four activator-ratio levels (3 × 4) was employed, resulting in 12 geopolymer mortar mixtures.

The response variables were density, water absorption, and compressive strength. Five specimens were prepared for each mixture for density and compressive strength testing, resulting in 60 observations for each response. Three specimens were prepared for each mixture for water absorption testing, resulting in 36 observations. The individual specimen measurements were retained as observations for statistical analysis, whereas mean values were used for descriptive presentation of the experimental results.

Materials

Fly ash obtained from the Jeranjang Coal-Fired Power Plant, West Lombok, Indonesia, was used as the primary precursor. Three locally available supplementary precursors, namely metakaolin, calcined clay, and rice husk ash (RHA), were used as partial replacements for fly ash. Natural sand obtained from Sesaot, West Lombok, Indonesia, was used as fine aggregate. Sodium hydroxide (NaOH) solution with a concentration of 12 M and sodium silicate (Na_2SiO_3) were used as alkaline activators.

Kaolin was calcined at 750 °C for approximately 12–24 h to produce metakaolin. Locally sourced clay was also calcined at 750 °C for approximately 12–24 h to improve its reactivity as a supplementary precursor. After calcination, the metakaolin and calcined clay were ground and sieved through a No. 200 sieve (75 µm). In contrast, RHA was obtained from the residual ash produced by the combustion of rice husks used as fuel in the brick or pottery firing process. Since the RHA had already undergone combustion during the firing process, no additional calcination treatment was applied. The RHA was directly ground and sieved through a No. 200 sieve (75 µm) before being used as a supplementary precursor.

Table 1. Experimental Variables

Parameter	Specification
Main precursor	Fly ash
Supplementary precursor	Metakaolin, Calcined Clay, Rice Husk Ash
Supplementary precursor content	20 wt.% of total precursor
Fly ash content	80 wt.% of total precursor
Binder : sand	1:1
Geopolymer paste : sand	50:50 wt.%
Precursor : alkaline activator	1:1 by mass
NaOH concentration	12 M
Alkaline activator ratio	NaOH : Na_2SiO_3 = 1:1.5, 1:2, 1:2.5, 1:3
Specimen size	50×50×50 mm
Testing age	28 days
Experimental design	Full factorial (3 × 4)

Figure 1. Calcined Process

Mix Design and Specimen Preparation

The geopolymer mortar mixtures were prepared with a total mass of 300 g per specimen. The mixture consisted of 150 g of fine aggregate and 150 g of geopolymer binder, corresponding to a binder-to-sand ratio of 1:1. The geopolymer binder consisted of 75 g of precursor and 75 g of alkaline activator, corresponding to a liquid-to-solid ratio of 1:1 by mass. The precursor consisted of 80 wt.% fly ash and 20 wt.% supplementary precursors, corresponding to 60 g of fly ash and 15 g of supplementary precursor.

Four alkaline activator ratios were investigated, namely $NaOH:Na_2SiO_3$ = 1:1.5, 1:2, 1:2.5, and 1:3. The total mass of alkaline activator was maintained at 75 g for all mixtures, while the masses of NaOH and Na_2SiO_3 were adjusted according to the specified ratio. Therefore, the NaOH and Na_2SiO_3 masses were 30.00 and 45.00 g for the 1:1.5 ratio, 25.00 and 50.00 g for the 1:2 ratio, 21.43 and 53.57 g for the 1:2.5 ratio, and 18.75 and 56.25 g for the 1:3 ratio, respectively.

The weighed materials were mixed using a mechanical mixer for approximately 5–10 min until a visually uniform mixture was obtained. The fresh mortar was then placed into the cube molds in three layers. Each layer was distributed evenly and compacted by approximately 10–15 manual tamping strokes before the next layer was added. The same procedure was applied to the second and third layers until the mold was completely filled and the mortar appeared sufficiently compact with no visible voids. The specimens were then left in the molds for approximately 24 h before demolding.

Table 2. Mix Design

Mixture	Precursor	Fly ash (g)	Supplementary precursor (g)	Sand (g)	NaOH (g)	Na_2SiO_3 (g)	Total (g)
MK-1	MK	60.00	15.00	150	30.00	45.00	300
MK-2	MK	60.00	15.00	150	25.00	50.00	300
MK-3	MK	60.00	15.00	150	21.43	53.57	300
MK-4	MK	60.00	15.00	150	18.75	56.25	300
CL-1	CL	60.00	15.00	150	30.00	45.00	300
CL-2	CL	60.00	15.00	150	25.00	50.00	300
CL-3	CL	60.00	15.00	150	21.43	53.57	300
CL-4	CL	60.00	15.00	150	18.75	56.25	300
RHA-1	RHA	60.00	15.00	150	30.00	45.00	300
RHA-2	RHA	60.00	15.00	150	25.00	50.00	300
RHA-3	RHA	60.00	15.00	150	21.43	53.57	300

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RHA-4	RHA	60.00	15.00	150	18.75	56.25	300

Curing Procedure

After approximately 24 h, the specimens were demolded and placed at room temperature under normal laboratory conditions without additional curing treatment. No water immersion, elevated-temperature curing, or other controlled curing treatment was applied. All specimens from the 12 mixture combinations were maintained under the same curing conditions for 28 days. After reaching the curing age of 28 days, the specimens were prepared for the corresponding physical and mechanical tests.

Figure 2. Curing Process

Testing Methods

The chemical compositions of the precursor materials were characterized using X-ray fluorescence (XRF). The density of the hardened geopolymer mortar was determined in accordance with SNI 1973:2008. Water absorption was measured according to SNI 03-2914-1992, while compressive strength was determined at 28 days in accordance with SNI 03-6825:2002.

Five specimens were tested for density and five specimens were tested for compressive strength for each mixture, resulting in 60 individual observations for each response across the 12 mixtures. Three specimens were tested for water absorption for each mixture, resulting in 36 individual observations. The individual measurements were retained for statistical analysis, while the mean values were used to summarize the experimental results.

Statistical Analysis

Statistical analysis was performed using Minitab 22 with a significance level of 5% ($\alpha = 0.05$). Individual specimen measurements were used as observations in the statistical analysis. The effects of supplementary precursor type, alkaline activator ratio, and their interaction were evaluated using a full-factorial Two-Way Analysis of Variance (Two-Way ANOVA).

Prior to ANOVA, the normality of each response dataset was evaluated using the Anderson–Darling test. Homogeneity of variance was assessed using Levene's test. A p-value greater than 0.05 was interpreted as indicating that the variance among treatment groups was homogeneous. For statistically significant main effects ($p < 0.05$), Tukey's Honestly Significant Difference (HSD) test was used for pairwise comparisons. Statistical significance was evaluated at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Chemical Composition of Raw Materials

The chemical compositions of the selected supplementary precursors were determined using X-ray fluorescence (XRF) to determine the major oxide constituents of each supplementary precursor. Three locally available supplementary precursors, namely metakaolin (MK), calcined clay (CL), and rice husk ash (RHA), were investigated to evaluate their effects under different alkaline activator ratios. The XRF results are summarized in Table 3.

Table 3. Chemical composition of raw materials determined by XRF

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	$\Sigma(SiO_2+Al_2O_3+Fe_2O_3)$
Fly ash	39.5	14.9	14.1	13.7	68.5
MK	64.6	28	2.95	0.454	95.55
CL	45.6	17.2	8.37	3.07	71.17
RHA	94.8	0.254	0.19	0.511	95.244

Metakaolin exhibited the highest combined content of SiO_2, Al_2O_3, and Fe_2O_3, followed by rice husk ash and calcined clay. The high silica contents of the investigated supplementary precursors indicate their potential to participate in the geopolymerization process, although their contributions differ according to their chemical composition and reactivity. During alkali activation, reactive aluminosilicate species dissolve and subsequently polymerize to form geopolymeric binding gels that contribute to strength development (Albidah et al., 2021; Logesh Kumar & Revathi, 2016).

Although all investigated supplementary precursors were rich in aluminosilicates, their oxide compositions differed considerably. These compositional differences are expected to influence the geopolymerization process under different alkaline activator ratios, thereby affecting the density, water absorption, and compressive strength of the resulting geopolymer mortar.

Therefore, the XRF results provide a chemical basis for interpreting the differences observed in the physical and mechanical properties of the geopolymer mortar. These differences are examined in the following sections based on density, water absorption, and compressive strength.

Table 4. Experimental results of the 12 geopolymer mortar mixtures

Mixture	Supplementary precursor	NaOH: Na_2SiO_3	Density (g/cm^3), Mean ± SD	Water absorption (%), Mean ± SD	Compressive strength (MPa), Mean ± SD
MK-1	Metakaolin	1:1.5	2.118 ± 0.030	5.748 ± 0.549	12.938 ± 1.704
MK-2	Metakaolin	1:2	2.126 ± 0.112	5.277 ± 0.345	13.463 ± 1.468
MK-3	Metakaolin	1:2.5	2.182 ± 0.078	4.504 ± 0.108	18.013 ± 1.566
MK-4	Metakaolin	1:3	2.153 ± 0.059	5.213 ± 0.281	17.653 ± 1.748
CL-1	calcined Clay	1:1.5	2.135 ± 0.036	5.435 ± 0.698	12.195 ± 1.920
CL-2	calcined Clay	1:2	2.153 ± 0.134	4.404 ± 0.552	13.412 ± 0.648
CL-3	calcined Clay	1:2.5	2.220 ± 0.027	3.807 ± 0.407	15.943 ± 2.315
CL-4	calcined Clay	1:3	2.200 ± 0.077	4.226 ± 0.379	14.814 ± 2.155
RHA-1	Rice husk ash	1:1.5	2.137 ± 0.022	4.977 ± 0.308	9.550 ± 0.735
RHA-2	Rice husk ash	1:2	2.149 ± 0.072	4.120 ± 0.253	11.030 ± 1.896
RHA-3	Rice husk ash	1:2.5	2.187 ± 0.063	3.897 ± 0.729	15.823 ± 0.702
RHA-4	Rice husk ash	1:3	2.167 ± 0.040	4.080 ± 0.605	12.606 ± 0.890

Table 4 summarizes the experimental results of the twelve geopolymer mortar mixtures investigated in this study. The results are presented as mean ± standard deviation based on the individual specimens tested for each mixture. The mixtures showed variations in density, water absorption, and compressive strength depending on the supplementary precursor and $NaOH:Na_2SiO_3$ ratio. In general, metakaolin-containing mixtures exhibited higher compressive strength than the calcined clay- and rice husk ash-containing mixtures, particularly at the 1:2.5 and 1:3 activator ratios. The experimental results were subsequently evaluated using statistical analysis to determine whether the observed differences were statistically significant. To examine the response of each measured property in greater detail, the experimental results are discussed separately for density, water absorption, and compressive strength in the following sections.

Density of Fly Ash-Based Geopolymer Mortar

The average density of fly ash-based geopolymer mortar incorporating different supplementary precursor types and $NaOH/Na_2SiO_3$ ratios is presented and illustrated in Figure 3.

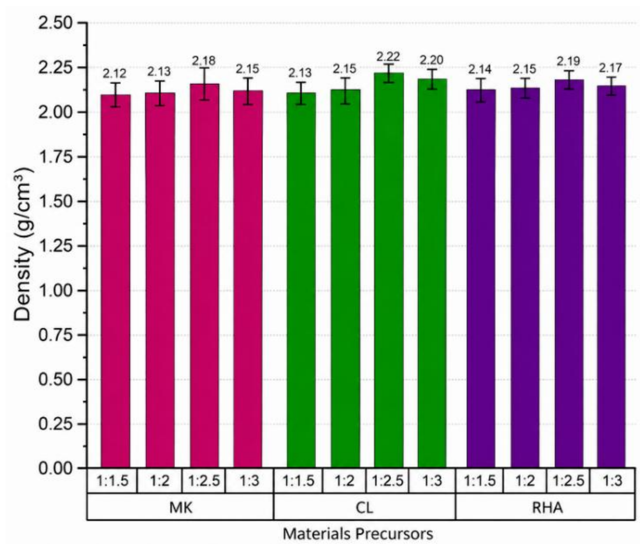

Figure 3. Density of fly ash-based geopolymer mortar. Error bars represent ± standard deviation.

Based on Fig. 3, the density of the geopolymer mortar ranged from 2.12 to 2.22 g/cm^3, indicating only slight variations among the investigated mixtures. For all supplementary precursors, density increased gradually as the $NaOH/Na_2SiO_3$ ratio increased from 1:1.5 to 1:2.5, followed by a slight decrease at the ratio of 1:3. The highest density (2.22 g/cm^3) was achieved by the calcined clay mixture at the $NaOH/Na_2SiO_3$ ratio of 1:2.5, whereas the lowest density (2.12 g/cm^3) was observed in the metakaolin mixture at the ratio of 1:1.5.

The slight variation in density observed with increasing $NaOH/Na_2SiO_3$ ratio may be associated with differences in matrix development and particle packing. However, these variations were relatively small and were not statistically significant according to the Two-Way ANOVA results. A sufficient amount of soluble silicate may enhance geopolymer gel formation, resulting in a more compact internal structure with fewer entrapped voids. A similar trend was reported by (Aslan & Erkan, 2024), who observed that improvements in geopolymer matrix development were accompanied by slight increases in density.

Despite the differences among the investigated mixtures, the variation in density remained relatively small compared with those observed for compressive strength and water absorption. This indicates that density is less sensitive to changes in supplementary precursor type and alkaline activator ratio than the other evaluated properties. Although calcined clay consistently exhibited the highest density, the differences among the investigated mixtures were relatively limited, suggesting that all mixtures produced geopolymer mortars with comparable compactness.

Overall, the density results indicate that the incorporation of different supplementary precursors and alkaline activator ratios produced only minor changes in the physical compactness of the geopolymer mortar. The statistical significance of these observations is further evaluated using Two-Way ANOVA.

Water Absorption of Fly Ash-Based Geopolymer Mortar

The average water absorption of fly ash-based geopolymer mortar incorporating different supplementary precursor types and $NaOH/Na_2SiO_3$ ratios is presented and illustrated in Figure 4.

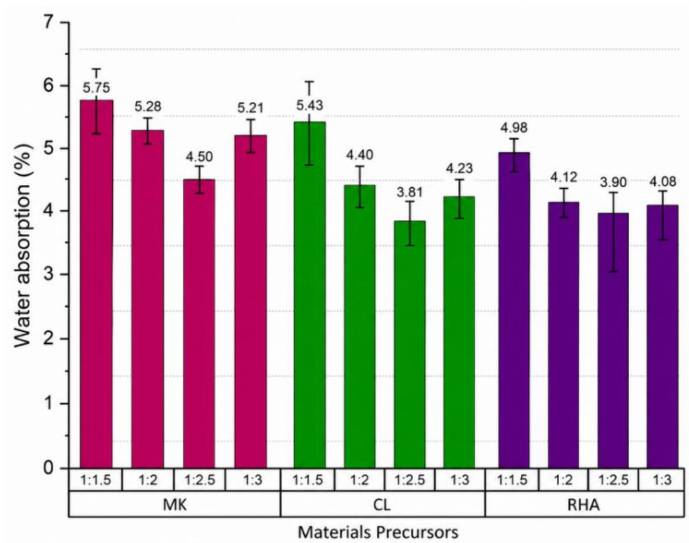

Figure 4. Water absorption of fly ash-based geopolymer mortar. Error bars represent ± standard deviation.

Based on Fig. 4, the water absorption of the geopolymer mortar was influenced by both the supplementary precursor type and the alkaline activator ratio. For all investigated mixtures, water absorption generally decreased as the $NaOH/Na_2SiO_3$ ratio increased from 1:1.5 to 1:2.5, followed by a slight increase at the ratio of 1:3. The lowest water absorption (3.81%) was obtained from the calcined clay mixture with a $NaOH/Na_2SiO_3$ ratio of 1:2.5, followed by rice husk ash (3.90%) and metakaolin (4.50%) at the same ratio. These results indicate that the $NaOH/Na_2SiO_3$ ratio of 1:2.5 was associated with the lowest observed water absorption across all three supplementary precursor types.

The reduction in water absorption with increasing $NaOH/Na_2SiO_3$ ratio may be associated with enhanced geopolymerization and matrix densification, which could reduce the accessibility of interconnected pores to water. A sufficient supply of soluble silicate facilitates the dissolution and polycondensation of reactive aluminosilicate species, resulting in improved matrix densification and lower permeability. Similar trends have been reported in previous studies (Zhu et al., 2019), who observed that an appropriate alkaline activator composition reduced pore connectivity and improved the impermeability of fly ash-based geopolymer materials. (Athira & Sathyan, 2026) also reported that a denser geopolymer matrix produced by reactive supplementary precursors significantly reduced water absorption.

Among the investigated supplementary precursors, clay exhibited the lowest water absorption despite not producing the highest compressive strength (Boakye & Khorami, 2023; Lekshmi et al., 2023). This finding suggests that the reduction in water absorption is governed primarily by matrix compactness and pore structure rather than compressive strength alone. Similar trends have been reported in previous studies (Matsimbe et al., 2024). The relatively fine particles of clay may have improved particle packing and reduced capillary pore connectivity, thereby limiting water penetration into the mortar (Boakye & Khorami, 2023; Lekshmi et al., 2023; Sharmin et al., 2024). Rice husk ash exhibited a comparable performance because its high reactive silica content promoted matrix refinement during geopolymerization, whereas metakaolin produced slightly higher water absorption despite exhibiting superior mechanical performance.

A comparison of the compressive strength and water absorption results reveals that the relationship between these properties is not entirely linear. Although the metakaolin mixture achieved the highest compressive strength, the calcined clay mixture exhibited the lowest water absorption. This observation indicates that compressive strength depends not only on pore refinement but also on precursor reactivity and the effectiveness of geopolymer gel formation. Consequently, the precursor that produces the strongest geopolymer matrix is not necessarily the one exhibiting the lowest water absorption. The statistical significance of these observations is discussed in the Two-Way ANOVA analysis.

Compressive Strength of Fly Ash-Based Geopolymer Mortar

The average compressive strength of fly ash-based geopolymer mortar incorporating different supplementary precursor types and $NaOH/Na_2SiO_3$ ratios is presented and illustrated in Figure 5.

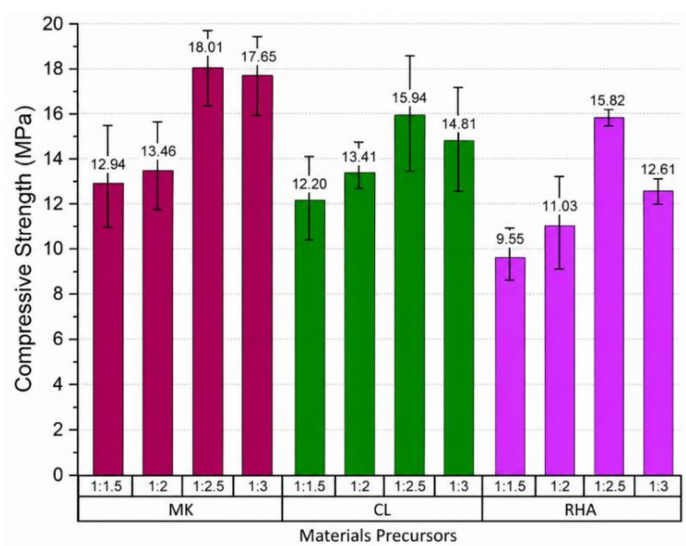

Figure 5. Compressive strength of fly ash-based geopolymer mortar. Error bars represent ± standard deviation.

Based on Fig. 5, both the supplementary precursor type and the alkaline activator ratio influenced the compressive strength of the geopolymer mortar. For all investigated precursors, the compressive strength increased as the $NaOH/Na_2SiO_3$ ratio increased from 1:1.5 to 1:2.5, followed by a slight decrease at the ratio of 1:3. Among all mixtures, the metakaolin mixture with a $NaOH/Na_2SiO_3$ ratio of 1:2.5 achieved the highest compressive strength (18.01 MPa), followed by calcined clay (15.94 MPa) and rice husk ash (15.82 MPa) at the same activator ratio. These results indicate that the $NaOH/Na_2SiO_3$ ratio of 1:2.5 produced the highest observed compressive strength among the investigated ratios for all supplementary precursors.

The improvement in compressive strength with increasing $NaOH/Na_2SiO_3$ ratio can be attributed to the greater availability of soluble silicate species, which promote the dissolution of reactive aluminosilicates and accelerate the formation of sodium aluminosilicate hydrate (N-A-S-H) gel. A denser and more continuous geopolymer matrix consequently develops, resulting in higher compressive strength. Similar observations have been reported in previous studies (Albidah et al., 2021; Aouan et al., 2021), who demonstrated that an appropriate alkaline activator composition enhances geopolymerization and improves the mechanical performance of geopolymer binders. However, increasing the $NaOH/Na_2SiO_3$ ratio from 1:2.5 to 1:3 slightly reduced compressive strength, suggesting that excessive sodium silicate may increase mixture viscosity and reduce the effectiveness of precursor dissolution and gel formation.

Among the investigated supplementary precursors, metakaolin consistently exhibited the highest compressive strength at all activator ratios. This difference in performance can be further related to the chemical characteristics of each supplementary precursor. This superior performance can be attributed to the high reactive aluminosilicate content of metakaolin, which facilitates dissolution during alkaline activation and promotes the formation of geopolymeric binding products (Albidah et al., 2021; Barbhuiya & Pang, 2022; Logesh Kumar & Revathi, 2016). In contrast, although calcined clay and rice husk ash also improved compressive strength, their performance remained lower than that of metakaolin because their mineralogical characteristics and precursor reactivity differed. Rice husk ash contains abundant reactive silica but relatively little alumina, whereas calcined clay generally exhibits lower reactivity than calcined metakaolin despite containing appreciable amounts of silica and alumina (Boakye & Khorami, 2023; Hwang & Huynh, 2015; Nana et al., 2021).

An interesting observation is that all three supplementary precursors exhibited a similar strength development pattern despite their different chemical compositions. The compressive strength increased progressively up to the $NaOH/Na_2SiO_3$ ratio of 1:2.5 before declining at the ratio of 1:3. This consistent trend suggests that the alkaline activator ratio governs the geopolymerization process in a similar manner for all investigated precursors, while the magnitude of strength development is primarily controlled by the intrinsic reactivity of each supplementary precursor. The statistical significance of these observations is further discussed in the Two-Way ANOVA analysis.

Statistical Analysis Result

The experimental data were statistically analyzed using Two-Way Analysis of Variance (Two-Way ANOVA) to evaluate the effects of supplementary precursor type, $NaOH/Na_2SiO_3$ ratio, and their interaction on the density, water absorption, and compressive strength of fly ash-based geopolymer mortar. Prior to the ANOVA, the normality of the datasets was evaluated using the Anderson–Darling test. All datasets exhibited p-values greater than 0.05, indicating that the data satisfied the normality assumption and were suitable for parametric analysis. The summary of the normality test is presented in Table 5.

Table 5. Results of the Anderson–Darling normality test.

Property	N	Anderson–Darling Statistic	p-value	Decision
Density	60	0.36	0.235	Normal
Water absorption	36	0.17	0.814	Normal
Compressive strength	60	0.28	0.456	Normal

After confirming that the response datasets satisfied the normality assumption, the homogeneity of variance was subsequently evaluated using Levene's test. The results are presented in Table 6.

Table 6. Results of the Levene's test for homogeneity of variance.

Parameter	Levene's Test Statistic	*p*-value	Decision
Density	1.528	0.153	Homogeneous
Water absorption	0.352	0.963	Homogeneous
Compressive strength	0.847	0.595	Homogeneous

The homogeneity of variance test showed that the variances among the 12 treatment combinations were homogeneous for all investigated parameters. Based on Levene's test using the median as the center, the test statistics were 1.528 ($p = 0.153$) for density, 0.352 ($p = 0.963$) for water absorption, and 0.847 ($p = 0.595$) for compressive strength. Since all p-values were greater than 0.05, the null hypothesis of equal variances was not rejected. Therefore, the homogeneity of variance assumption was satisfied for the subsequent Two-Way ANOVA.

The results of the Two-Way ANOVA are summarized in Table 7. The analysis revealed that the effects of supplementary precursor type and activator ratio varied depending on the evaluated property.

Table 7. Results of the Two-Way ANOVA.

Response	Source	F-value	p-value	Decision
Density	Supplementary precursor	1.03	0.393	Not significant
	$NaOH/Na_2SiO_3$ ratio	2.67	0.068	Not significant
	Interaction	0.10	0.996	Not significant
Water absorption	Supplementary precursor	12.54	<0.001	Significant
	$NaOH/Na_2SiO_3$ ratio	12.17	<0.001	Significant
	Interaction	1.37	0.259	Not significant
Compressive strength	Supplementary precursor	21.36	<0.001	Significant
	$NaOH/Na_2SiO_3$ ratio	31.05	<0.001	Significant
	Interaction	1.72	0.142	Not significant

As shown in Table 7, neither supplementary precursor type nor activator ratio significantly affected the density of geopolymer mortar ($p > 0.05$). In contrast, both factors significantly influenced water absorption and compressive strength ($p < 0.05$). However, the interaction between supplementary precursor type and activator ratio was not statistically significant for any of the evaluated properties. These findings indicate that the effects of precursor type and activator ratio were not significantly dependent on each other within the experimental range investigated.

To further identify the significant differences among factor levels, Tukey's Honestly Significant Difference (HSD) post hoc test was performed for the significant main effects.

Table 8. Results of Tukey's HSD multiple comparison test.

Response	Factor	Highest-performing group	Mean	Grouping	Interpretation
Compressive strength	Supplementary precursor	Metakaolin	15.52	A	Significantly higher than calcined clay and RHA
	$NaOH/Na_2SiO_3$ ratio	1:2.5	16.59	A	Significantly higher than all other ratios
Water absorption	Supplementary precursor	calcined Clay	4.47	B	Not significantly different from RHA, but significantly lower than MK
	$NaOH/Na_2SiO_3$ ratio	1:2.5	4.07	B	Significantly lower than 1:1.5

The Tukey HSD results confirmed the findings of the Two-Way ANOVA. For compressive strength, metakaolin formed a distinct statistical group with the highest mean value, indicating superior mechanical performance compared with calcined clay and rice husk ash. Similarly, the $NaOH/Na_2SiO_3$ ratio of 1:2.5 produced the highest compressive strength and differed significantly from the other activator ratios. For water absorption, calcined clay and rice husk ash exhibited significantly lower values than metakaolin. For density, the ANOVA results indicated that neither supplementary precursor type nor $NaOH/Na_2SiO_3$ ratio produced a significant effect.

CONCLUSION

This study investigated the effects of supplementary precursor type (metakaolin, calcined clay, and rice husk ash) and $NaOH/Na_2SiO_3$ ratio on the physical and mechanical properties of fly ash-based geopolymer mortar. The experimental results showed that a $NaOH/Na_2SiO_3$ ratio of 1:2.5 produced the highest observed compressive strength and generally the lowest water absorption among the investigated ratios, while variations in density remained relatively small.

The Two-Way ANOVA results demonstrated that supplementary precursor type and $NaOH/Na_2SiO_3$ ratio significantly affected water absorption and compressive strength ($p < 0.05$), whereas neither factor significantly affected density ($p > 0.05$). The interaction between supplementary precursor type and $NaOH/Na_2SiO_3$ ratio was not statistically significant for density, water absorption, or compressive strength ($p > 0.05$). These findings indicate that the effects of the two factors were statistically independent within the investigated experimental range.

Among the investigated combinations, metakaolin with a $NaOH/Na_2SiO_3$ ratio of 1:2.5 achieved the highest observed compressive strength of 18.01 MPa, with a density of 2.18 g/cm^3 and water absorption of 4.50%. Meanwhile, the calcined clay mixture at the same ratio exhibited the highest observed density of 2.22 g/cm^3 and the lowest observed water absorption of 3.81%. Tukey's HSD analysis further confirmed significant differences among the levels of supplementary precursor type and $NaOH/Na_2SiO_3$ ratio for compressive strength and water absorption. Therefore, within the investigated experimental conditions, metakaolin combined with a $NaOH/Na_2SiO_3$ ratio of 1:2.5 provided the highest observed compressive strength, whereas calcined clay combined with the same ratio provided the lowest observed water absorption.

REFERENCES

Albidah, A., Alghannam, M., Abbas, H., Almusallam, T., & Al-Salloum, Y. (2021). Characteristics of metakaolin-based geopolymer concrete for different mix design parameters. *Journal of Materials Research and Technology*, *10*, 84–98. https://doi.org/10.1016/j.jmrt.2020.11.104

Aouan, B., Alehyen, S., Fadil, M., EL Alouani, M., Khabbazi, A., Atbir, A., & Taibi, M. (2021). Compressive strength optimization of metakaolin-based geopolymer by central composite design. *Chemical Data Collections*, *31*. https://doi.org/10.1016/j.cdc.2020.100636

Archer de Carvalho, T., Gaspar, F., Marques, A. C., & Mateus, A. (2024). Optimization of formulation ratios of geopolymer mortar based on metakaolin and biomass fly ash. *Construction and Building Materials*, *412*. https://doi.org/10.1016/j.conbuildmat.2023.134846

Aslan, S., & Erkan, İ. H. (2024). The Effects of Fly Ash, Blast Furnace Slag, and Limestone Powder on the Physical and Mechanical Properties of Geopolymer Mortar. *Applied Sciences (Switzerland)*, *14*(2). https://doi.org/10.3390/app14020553

ASTM International. (2019). *ASTM C618/C618M-19: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*. West Conshohocken, PA: ASTM International. https://doi.org/10.1520/C0618_C0618M-19

Athira, R., & Sathyan, D. (2026). Data-driven optimization of fly ash–slag–rice husk ash geopolymer systems via particle packing and thermodynamic simulation. *Journal of Asian Architecture and Building Engineering*. https://doi.org/10.1080/13467581.2026.2665973

Barbhuiya, S., & Pang, E. (2022). Strength and Microstructure of Geopolymer Based on Fly Ash and Metakaolin. *Materials*, *15*(10). https://doi.org/10.3390/ma15103732

Boakye, K., & Khorami, M. (2023). Impact of Low-Reactivity Calcined Clay on the Performance of Fly Ash-Based Geopolymer Mortar. *Sustainability (Switzerland)*, *15*(18). https://doi.org/10.3390/su151813556

Davidovits, J. (2020). *Geopolymer chemistry and applications* (5th ed.). Geopolymer Institute.

Hadi, M. N. S., Al-Azzawi, M., & Yu, T. (2018). Effects of fly ash characteristics and alkaline activator components on compressive strength of fly ash-based geopolymer mortar. *Construction and Building Materials*, *175*, 41–54. https://doi.org/10.1016/J.CONBUILDMAT.2018.04.092

Hwang, C. L., & Huynh, T. P. (2015). Effect of alkali-activator and rice husk ash content on strength development of fly ash and residual rice husk ash-based geopolymers. *Construction and Building Materials*, *101*, 1–9. https://doi.org/10.1016/j.conbuildmat.2015.10.025

Karyawan, I. D. M. A., Yuniarti, R., Hasyim, H., & Widianty, D. (2022). Characteristics of fly ash geopolymer based on alkaline ratio of activators for building materials: A review. *Teknika: Jurnal Sains dan Teknologi*, *18*(1), 18–22. https://doi.org/10.36055/tjst.v18i1.15410

Lehne, J., & Preston, F. (2018). *Making concrete change: Innovation in low-carbon cement and concrete*. Chatham House.

Lekshmi, S., Sudhakumar, J., & Thomas, S. (2023). Durability performance of geopolymer mortar containing high calcium fly ash and low-grade waste clay. *Asia-Pacific Journal of Science and Technology*, *28*(2), APST–28. https://doi.org/10.14456/apst.2023.20

Logesh Kumar, M., & Revathi, V. (2016). Metakaolin bottom ash blend geopolymer mortar - A feasibility study. *Construction and Building Materials*, *114*, 1–5. https://doi.org/10.1016/j.conbuildmat.2016.03.149

Matsimbe, J., Dinka, M., Olukanni, D., & Musonda, I. (2024). Durability properties of ambient-cured fly ash-phosphogypsum blended geopolymer mortar in terms of water absorption, porosity, and sulfate resistance. *Discover Sustainability*, *5*(1). https://doi.org/10.1007/s43621-024-00537-3

Montgomery, D. C. (2019). *Design and analysis of experiments* (10th ed.). John Wiley & Sons.

Mulapeer, E. M., & Omar, A. H. (2025). Durability and mechanical performance of geopolymer mortar with partial replacement of fly ash by rice husk ash and variations in alkaline activator concentrations. *Discover Civil Engineering*, *2*, Article 82. https://doi.org/10.1007/s44290-025-00234-8

Nana, A., Epey, N., Rodrique, K. C., Deutou, J. G. N., Djobo, J. N. Y., Tomé, S., Alomayri, T. S., Ngouné, J., Kamseu, E., & Leonelli, C. (2021). Mechanical strength and microstructure of metakaolin/volcanic ash-based geopolymer composites reinforced with reactive silica from rice husk ash (RHA). *Materialia*, *16*. https://doi.org/10.1016/j.mtla.2021.101083

Harmaji, A., Haimir, A. S., & Sunendar, B. (2023). Impact of reduced activator concentration and curing method on compressive strength of metakaolin/fly ash-based geopolymer mortar. *Jurnal Riset Teknologi Pencegahan Pencemaran Industri*, *14*(1), 19–28. https://doi.org/10.21771/jrtppi.2023.v14.no.1.p19-28

Sharmin, S., Sarker, P. K., Biswas, W. K., Abousnina, R. M., & Javed, U. (2024). Characterization of waste clay brick powder and its effect on the mechanical properties and microstructure of geopolymer mortar. *Construction and Building Materials*, *412*. https://doi.org/10.1016/j.conbuildmat.2023.134848

Zahid, M., Shafiq, N., Nuruddin, M. F., Nikbakht, E., & Jalal, A. (2017). Effect of partial replacement of fly ash by metakaolin on strength development of fly ash based geopolymer mortar. *Key Engineering Materials*, *744 744 KEM*, 131–135. https://doi.org/10.4028/www.scientific.net/KEM.744.131

Zhu, H., Liang, G., Xu, J., Wu, Q., & Zhai, M. (2019). Influence of rice husk ash on the waterproof properties of ultrafine fly ash based geopolymer. *Construction and Building Materials*, *208*, 394–401. https://doi.org/10.1016/j.conbuildmat.2019.03.035