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Effect of Liquid-to-Solid (L/S) Ratio on The Characteristics of Metakaolinbased Geopolymer Mortar for Lightweight Panel Applications

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Keywords
Geopolymer Mortar; Metakaolin; Liquid-To-Solid Ratio; Compressive Strength; Density; Water Absorption; One-Way ANOVA

ABSTRACT
The development of low-carbon construction materials has become increasingly important to mitigate the environmental impacts associated with the extensive use of Portland cement. Metakaolin-based geopolymer mortar has emerged as a promising alternative binder due to its environmental advantages and favorable engineering properties. This study aimed to determine the optimum liquid-to-solid (L/S) ratio and evaluate its effects on the compressive strength, density, and water absorption of metakaolin-based geopolymer mortar. An experimental laboratory investigation was conducted using five liquid-to-solid (L/S) ratios of 0.40, 0.45, 0.50, 0.55, and 0.60. The evaluated properties included compressive strength, density, and water absorption. Statistical significance was assessed using a one-way analysis of variance (ANOVA).The L/S ratio significantly influenced all measured properties. The optimum performance was achieved at an L/S ratio of 0.45, which resulted in the highest compressive strength (16.60 MPa), the highest density (1.96 g/cm³), and the lowest water absorption (4%). One-way ANOVA confirmed that the L/S ratio had a significant effect on compressive strength, density, and water absorption ($p < 0.001$). The liquid-to-solid ratio was identified as a critical parameter governing microstructural densification, porosity development, and the physical and mechanical properties of metakaolin-based geopolymer mortar. An L/S ratio of 0.45 was recommended as the optimum condition for achieving balanced mechanical performance and durability-related properties.

INTRODUCTION

The construction industry is one of the largest contributors to global carbon emissions due to the extensive use of Portland cement as the primary binder in concrete and mortar production (Adesina, 2020; Gonnon & Lootens, 2023; Habert et al., 2020; Miller et al., 2018; Shah et al., 2022). Cement manufacturing generates substantial carbon dioxide emissions through limestone calcination and high energy consumption during the production process. These environmental concerns have encouraged the development of more sustainable alternative binders, among which geopolymers have emerged as a promising solution (Davidovits, 2013). Geopolymers are inorganic binder materials formed through the reaction between aluminosilicate precursors and alkaline activator solutions, producing a hardened matrix with properties comparable to conventional cement-based materials (Duxson et al., 2007). Compared with Portland cement, geopolymers offer the potential for reduced carbon emissions while maintaining favorable mechanical performance and chemical resistance. Among various aluminosilicate precursors, metakaolin has been widely utilized in geopolymer production due to its high amorphous silica and alumina contents, high reactivity in alkaline environments, and ability to form relatively homogeneous and stable geopolymer structures (Tchakouté & Rüscher, 2017). In addition to precursor characteristics, the performance of geopolymer materials is strongly influenced by mixture parameters, particularly the liquid-to-solid (L/S) ratio, which governs the dissolution of silica and alumina species, geopolymer gel formation, porosity development, and the resulting physical and mechanical properties of the material (Panagiotopoulou et al., 2007; Heah et al., 2012).

Several studies have investigated the effects of the liquid-to-solid (L/S) ratio on geopolymer properties. Heah et al. (2012) found that the L/S ratio significantly influenced the compressive strength and microstructure of kaolin-based geopolymers, with an optimum ratio being essential for sufficient dissolution of aluminosilicate precursors and the formation of a dense matrix. However, excessive liquid content increased porosity and reduced mechanical performance. Jaya et al. (2018) reported that variations in the L/S ratio affected the compressive strength, density, and setting time of metakaolin geopolymers, with lower ratios producing higher strength due to denser matrix formation, whereas higher ratios reduced strength due to the formation of voids from excess unreacted water. Jamaludin et al. (2023) revealed that the L/S ratio played a critical role in determining the adhesion properties of metakaolin geopolymer coating paste, with optimum performance achieved at specific proportions. Meanwhile, Razak et al. (2020) demonstrated that reduced porosity and water absorption contributed to improved compressive strength through the formation of denser structures in fly ash-based geopolymers.

For lightweight panel applications, the performance of geopolymer mortar is determined not only by compressive strength but also by density and water absorption, which influence weight efficiency and long-term service performance (Kioupis et al., 2022; Koçyiğit, 2024; Longo et al., 2020; Przybek et al., 2025; Rathinavel et al., 2025; Raza et al., 2025). An excessively low L/S ratio may hinder the geopolymerization process due to an insufficient reaction medium, whereas an excessively high L/S ratio may increase porosity due to excess liquid evaporation during hardening (Heah et al., 2012). These conditions directly affect material density, water absorption capacity, and load-bearing performance. Therefore, the development of lightweight geopolymer materials for panel and non-structural applications requires an appropriate balance between mechanical and physical properties to achieve optimal performance (Novais et al., 2020).

Although the influence of the L/S ratio on geopolymer materials has been extensively investigated, most studies have primarily focused on compressive strength as the main performance indicator. Studies evaluating the simultaneous effects of the L/S ratio on compressive strength, density, and water absorption of metakaolin-based geopolymer mortar for lightweight panel applications remain limited. Furthermore, the application of inferential statistical approaches to verify the significance of the L/S ratio on geopolymer mortar characteristics has received relatively limited attention.

Therefore, this study aimed to investigate the effect of the liquid-to-solid (L/S) ratio on the compressive strength, density, and water absorption of geopolymer mortar produced from locally sourced Lombok metakaolin, as well as to evaluate the statistical significance of this parameter using one-way analysis of variance (ANOVA). This research contributes to the development of lightweight metakaolin-based geopolymer mortar for sustainable construction applications and provides statistical evidence to support the optimization of the L/S ratio in geopolymer mix design.

METHOD

This study employed a laboratory experimental approach to investigate the effect of the liquid-to-solid (L/S) ratio on the characteristics of metakaolin-based geopolymer mortar. The experimental design used a single-factor approach, with the L/S ratio as the independent variable. Five L/S ratios were evaluated: 0.40, 0.45, 0.50, 0.55, and 0.60. All other mixture parameters were maintained consistently to ensure that variations in material properties were attributed to differences in the L/S ratio.

The alkaline activator solution was prepared by dissolving sodium hydroxide in water and adding sodium silicate to obtain a homogeneous solution. Metakaolin and sand were dry-mixed using a laboratory mixer, followed by the gradual addition of the activator solution until a homogeneous geopolymer mortar was obtained. The fresh mortar was cast into molds and compacted before being cured under predetermined conditions. After reaching the specified curing age, the specimens were prepared for material characterization.

The investigated properties included compressive strength, density, and water absorption. Compressive strength testing was conducted to evaluate the mechanical performance of the geopolymer mortar, while density and water absorption tests were performed to assess its physical characteristics.

The experimental data were analyzed using one-way analysis of variance (ANOVA) to determine the statistical significance of the effect of the liquid-to-solid (L/S) ratio on the compressive strength, density, and water absorption of metakaolin-based geopolymer mortar. This analysis was used to identify whether differences among mixture variations were statistically significant.

RESULT AND DISCUSSION

Effect of Liquid-to-Solid (L/S) Ratio on the Characteristics of Geopolymer Mortar

The experimental results indicate that the liquid-to-solid (L/S) ratio significantly influences the compressive strength of metakaolin-based geopolymer mortar. As illustrated in Figure 1, the compressive strength increased from 9.14 MPa at an L/S ratio of 0.40 to 16.60 MPa at an L/S ratio of 0.45, followed by a decline to 7.27 MPa, 5.00 MPa, and 3.20 MPa at L/S ratios of 0.50, 0.55, and 0.60, respectively. These results identify 0.45 as the optimum L/S ratio. The increase in compressive strength up to the optimum level suggests that the amount of activator solution was sufficient to promote the dissolution of silica and alumina from metakaolin and facilitate the formation of N–A–S–H gel, which serves as the primary binding phase in geopolymer systems.

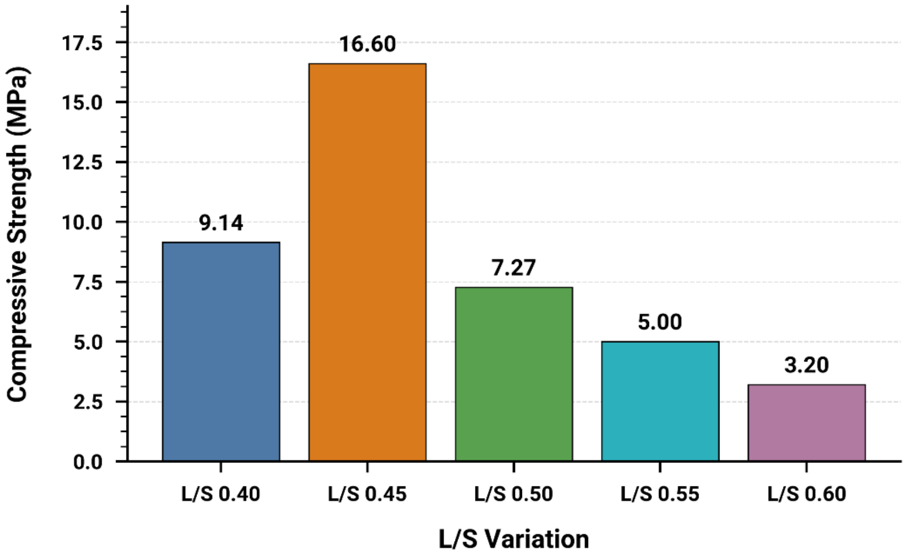

Figure 1. Relationship between Liquid-to-Solid (L/S) Ratio and Compressive Strength of Metakaolin-Based Geopolymer Mortar

Source: Laboratory test results, 2026

At an L/S ratio of 0.45, the geopolymerization process is presumed to proceed more efficiently, resulting in a denser and more homogeneous matrix than those produced at other mixture proportions. In contrast, increasing the L/S ratio beyond the optimum level led to a substantial reduction in compressive strength. This behavior indicates that excess liquid generated free water within the mixture, which evaporated during curing and left voids within the hardened matrix. The resulting increase in porosity reduced the effective load-bearing area, thereby decreasing the compressive strength of the mortar. These findings suggest that the compressive performance of geopolymer mortar is strongly governed by the balance between activator availability for geopolymerization and porosity development during hardening.

A similar trend was observed in the density results. As shown in Figure 2, the density increased from 1.85 g/cm^3 at an L/S ratio of 0.40 to 1.96 g/cm^3 at an L/S ratio of 0.45, before decreasing to 1.82 g/cm^3, 1.80 g/cm^3, and 1.77 g/cm^3 at L/S ratios of 0.50, 0.55, and 0.60, respectively. The highest density obtained at an L/S ratio of 0.45 indicates that this condition promoted the most effective matrix densification. The increase in density suggests the formation of a more compact internal structure due to a more efficient geopolymerization process.

The reduction in density at higher L/S ratios indicates that increasing liquid content promotes the formation of additional internal voids within the mortar. During curing, excess water that does not participate in geopolymerization evaporates and leaves behind pores, thereby increasing the overall porosity of the material. As a result, the mortar becomes less compact and exhibits a lower density. Therefore, density can be considered an indirect indicator of microstructural quality and the degree of matrix compactness achieved under different L/S ratios.

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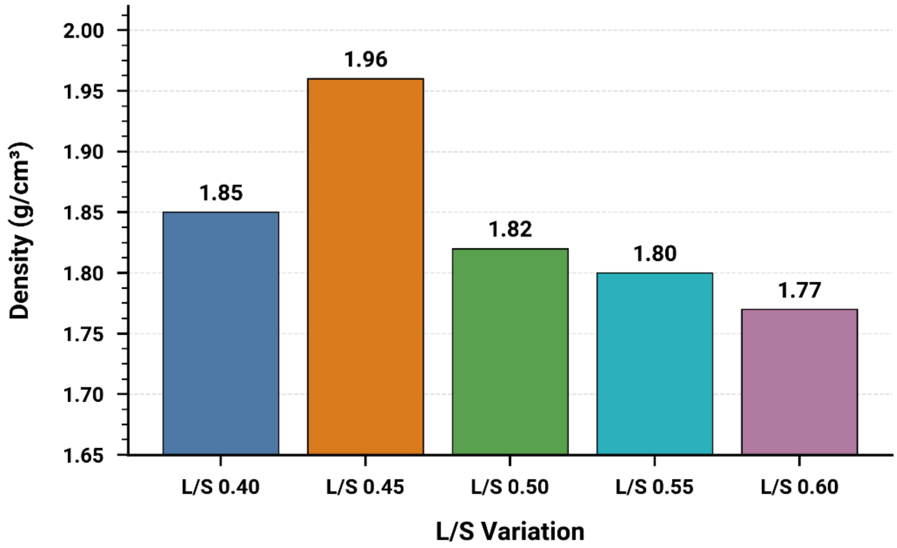

Figure 2. Relationship between Liquid-to-Solid (L/S) Ratio and Density of Metakaolin-Based Geopolymer Mortar

Source: Laboratory test results, 2026

The influence of the L/S ratio was also evident in the water absorption behavior of the geopolymer mortar. As presented in Figure 3, the lowest water absorption value was obtained at an L/S ratio of 0.45 (4%), whereas the highest value was recorded at an L/S ratio of 0.60 (12%). Water absorption values of 6%, 8%, and 9% were observed at L/S ratios of 0.40, 0.50, and 0.55, respectively. These results indicate that the water absorption capacity of the mortar is strongly dependent on the quantity and distribution of pores within the geopolymer matrix.

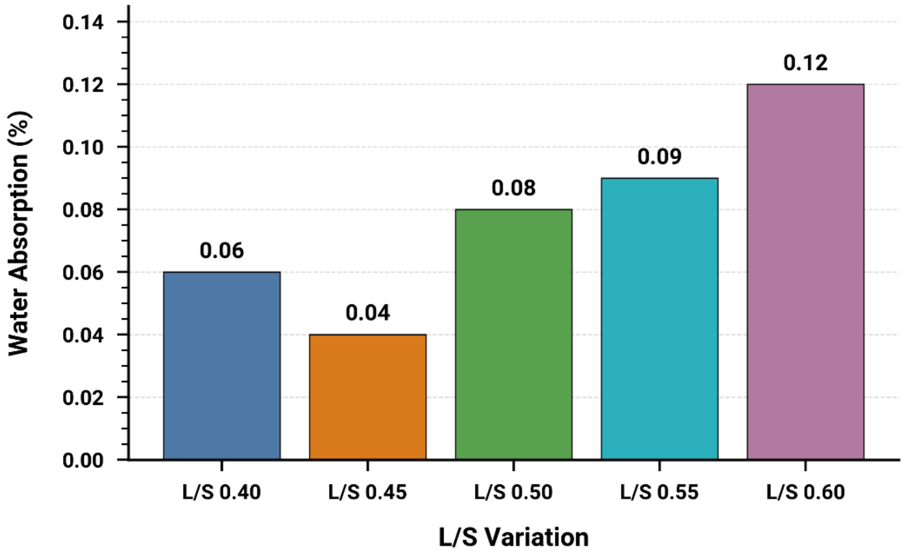

Figure 3. Relationship between Liquid-to-Solid (L/S) Ratio and Water Absorption of Metakaolin-Based Geopolymer Mortar

Source: Laboratory test results, 2026

The low water absorption observed at the optimum L/S ratio suggests the formation of a denser matrix with fewer interconnected pores. Conversely, increasing the L/S ratio resulted in the formation of additional voids and capillary pathways, facilitating water penetration into the material. Consequently, water absorption increased progressively with increasing L/S ratio.

These findings indicate that controlling the L/S ratio not only affects the mechanical performance of geopolymer mortar but also plays a critical role in determining microstructural quality and durability-related physical properties.

The three investigated properties exhibited a strong interrelationship governed by the quality of the geopolymer microstructure. The optimum L/S ratio of 0.45 produced the highest compressive strength (16.60 MPa), the highest density (1.96 g/cm^3), and the lowest water absorption (4%). These results indicate that this mixture proportion generated the densest and most homogeneous geopolymer matrix among all tested compositions. In general, higher density was associated with higher compressive strength and lower water absorption, whereas increased water absorption corresponded to reductions in both density and compressive strength.

This relationship suggests that internal porosity is the primary factor controlling the physical and mechanical characteristics of metakaolin-based geopolymer mortar. Similar observations were reported by Razak et al. (2020), who demonstrated that reduced porosity and water absorption contribute to improved compressive strength due to the formation of a denser geopolymer structure. Furthermore, Heah et al. (2012) reported that an optimum liquid-to-solid ratio enhances geopolymerization and promotes better microstructural densification. Therefore, the present findings confirm that controlling the L/S ratio is essential for achieving an appropriate balance between compressive strength, density, and water absorption in metakaolin-based geopolymer mortar.

Statistical Analysis Using One-Way ANOVA

The One-Way ANOVA results revealed that the liquid-to-solid (L/S) ratio had a highly significant effect on the compressive strength of metakaolin-based geopolymer mortar. As shown in Figure 4, an F-value of 710.41 was obtained with a significance level of $p < 0.001$. These results indicate that the null hypothesis was rejected, confirming that variations in the L/S ratio produced statistically significant differences in compressive strength. The exceptionally high F-value suggests that the observed variation in compressive strength was primarily attributed to changes in the L/S ratio rather than random experimental variability. Therefore, the L/S ratio can be considered the dominant factor controlling the mechanical performance of metakaolin-based geopolymer mortar.

The results of Tukey's post-hoc test further demonstrated that all L/S ratio levels belonged to different statistical groups, indicating that each variation produced a significantly different compressive strength response. The highest compressive strength was achieved at an L/S ratio of 0.45 (16.60 MPa), while the lowest value was recorded at an L/S ratio of 0.60 (3.20 MPa). These findings reinforce the experimental observations that an L/S ratio of 0.45 represents the optimum condition, providing the best balance between activator availability and the formation of a dense geopolymer matrix. In contrast, increasing the L/S ratio beyond the optimum level promoted greater internal porosity, resulting in a significant reduction in compressive strength.

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One-way ANOVA: L/S 0,40; L/S 0,45; L/S 0,50; L/S 0,55; L/S 0,60

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0,05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	5	L/S 0,40; L/S 0,45; L/S 0,50; L/S 0,55; L/S 0,60

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	4	537,530	134,382	710,41	0,000
Error	20	3,783	0,189		
Total	24	541,313			

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
L/S 0,45	5	16,600	A
L/S 0,40	5	9,140	B
L/S 0,50	5	7,274	C
L/S 0,55	5	5,004	D
L/S 0,60	5	3,200	E

Means that do not share a letter are significantly different.

Figure 4. One-Way ANOVA Results of the Effect of Liquid-to-Solid (L/S) Ratio on the Compressive Strength of Metakaolin-Based Geopolymer Mortar

Source: Statistical analysis using SPSS/statistical software, 2026

The One-Way ANOVA results for density also confirmed a significant effect of the L/S ratio on the physical characteristics of the geopolymer mortar. As illustrated in Figure 5, an F-value of 19.02 with $p < 0.001$ was obtained, indicating statistically significant differences among the tested mixtures. Although the magnitude of the effect was lower than that observed for compressive strength, the results demonstrate that the liquid content of the mixture plays an important role in controlling internal structure development and matrix densification.

Based on the average test results, the highest density was obtained at an L/S ratio of 0.45 (1.962 g/cm^3), whereas the lowest density was observed at an L/S ratio of 0.60 (1.768 g/cm^3). Tukey's post-hoc analysis revealed that the L/S ratio of 0.45 formed a distinct statistical group with the highest density, indicating the formation of the most compact and homogeneous geopolymer matrix. The reduction in density at higher L/S ratios suggests an increase in internal voids caused by excess liquid that did not participate in geopolymerization and subsequently evaporated during curing. This phenomenon resulted in a less dense material and showed a consistent relationship with the compressive strength trend observed previously.

One-way ANOVA: L/S 0,40; L/S 0,45; L/S 0,50; L/S 0,55; L/S 0,60

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0,05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	5	L/S 0,40; L/S 0,45; L/S 0,50; L/S 0,55; L/S 0,60

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	4	0,11126	0,027814	19,02	0,000
Error	20	0,02924	0,001462		
Total	24	0,14050			

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping		
L/S 0,45	5	1,9620	A		
L/S 0,40	5	1,8500		B	
L/S 0,50	5	1,8180		B	C
L/S 0,55	5	1,80000		B	C
L/S 0,60	5	1,7680			C

Means that do not share a letter are significantly different.

Figure 5. One-Way ANOVA Results of the Effect of Liquid-to-Solid (L/S) Ratio on the Density of Metakaolin-Based Geopolymer Mortar

Source: Statistical analysis using SPSS/statistical software, 2026

The effect of the L/S ratio on water absorption was also found to be statistically significant. As presented in Figure 6, an F-value of 12.06 with $p < 0.001$ was obtained, indicating that variations in the L/S ratio produced significant differences in water absorption behavior. Since the null hypothesis was rejected, it can be concluded that the L/S ratio significantly influences the water absorption capacity of geopolymer mortar. These findings confirm that the pore structure developed during geopolymerization is strongly dependent on the amount of liquid incorporated into the mixture.

The lowest water absorption value was obtained at an L/S ratio of 0.45 (4.4%), whereas the highest value was recorded at an L/S ratio of 0.60 (12.4%). Tukey's post-hoc test showed that higher L/S ratios tended to belong to groups with significantly greater water absorption. This behavior indicates that increasing liquid content promotes the formation of interconnected pores and capillary channels that facilitate water penetration into the material. Conversely, the optimum L/S ratio of 0.45 produced a more compact matrix structure, thereby reducing water absorption. These findings further confirm that water absorption is a sensitive indicator of changes in geopolymer microstructural quality.

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One-way ANOVA: L/S 0,40; L/S 0,45; L/S 0,50; L/S 0,55; L/S 0,60

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0,05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	5	L/S 0,40; L/S 0,45; L/S 0,50; L/S 0,55; L/S 0,60

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	4	0,019296	0,004824	12,06	0,000
Error	20	0,008000	0,000400		
Total	24	0,027296			

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping		
L/S 0,60	5	0,12400	A		
L/S 0,55	5	0,0920	A	B	
L/S 0,50	5	0,08000		B	C
L/S 0,40	5	0,05800		B	C
L/S 0,45	5	0,04400			C

Means that do not share a letter are significantly different.

Figure 6. One-Way ANOVA Results of the Effect of Liquid-to-Solid (L/S) Ratio on the Water Absorption of Metakaolin-Based Geopolymer Mortar

Source: Statistical analysis using SPSS/statistical software, 2026

Overall, the statistical analysis demonstrates that the liquid-to-solid (L/S) ratio significantly affects all investigated characteristics of metakaolin-based geopolymer mortar, namely compressive strength, density, and water absorption. All parameters exhibited significance levels of $p < 0.001$, confirming that the observed differences were attributable to variations in the L/S ratio rather than random experimental fluctuations. The L/S ratio of 0.45 consistently produced the highest compressive strength, highest density, and lowest water absorption, indicating the most effective geopolymerization process and the densest matrix structure among the investigated mixtures.

These findings are consistent with the study of Heah et al. (2012), who reported that the liquid-to-solid ratio is a critical parameter governing microstructural development and the mechanical performance of metakaolin-based geopolymers. Similar observations were reported by Razak et al. (2020), who demonstrated that reduced porosity and water absorption contribute to improved compressive strength through the formation of a denser geopolymer structure. Therefore, the statistical analysis not only validates the experimental findings but also confirms that controlling the L/S ratio is a key factor in the development of metakaolin-based geopolymer mortar for lightweight panel applications and sustainable construction materials.

CONCLUSION

This study was conducted to evaluate the effect of the liquid-to-solid (L/S) ratio on the characteristics of metakaolin-based geopolymer mortar using descriptive and inferential analytical approaches. Based on the findings, the following conclusions were drawn. First, the descriptive analysis demonstrated that the liquid-to-solid (L/S) ratio significantly influenced the compressive strength, density, and water absorption of metakaolin-based geopolymer mortar. An L/S ratio of 0.45 produced the optimum performance, achieving the highest compressive strength (16.60 MPa), highest density (1.96 g/cm^3), and lowest water absorption (4%). These results indicated that an L/S ratio of 0.45 provided the most favorable balance between activator availability, geopolymerization efficiency, and microstructural densification. The relationship among the three parameters showed that higher density was generally associated with increased compressive strength and reduced water absorption, suggesting that internal porosity was a primary factor governing the physical and mechanical performance of metakaolin-based geopolymer mortar.

Second, inferential analysis using one-way analysis of variance (ANOVA) confirmed that the liquid-to-solid (L/S) ratio had a statistically significant effect on all investigated parameters, including compressive strength ($F = 710.41$; $p < 0.001$), density ($F = 19.02$; $p < 0.001$), and water absorption ($F = 12.06$; $p < 0.001$). Tukey's post-hoc test further revealed significant differences among the mixture variations, with an L/S ratio of 0.45 consistently exhibiting superior performance compared with the other tested ratios. These findings confirmed that the liquid-to-solid ratio was a key parameter controlling microstructural development, density, porosity, and the overall performance of metakaolin-based geopolymer mortar. Therefore, optimizing the L/S ratio was essential for developing sustainable lightweight panel materials and other geopolymer-based construction applications.

Based on the findings and limitations of this study, several recommendations are proposed. Future research should evaluate additional mechanical properties, such as flexural and tensile strength, as well as durability aspects, including chemical resistance and thermal stability. The effects of other parameters, such as activator concentration, curing temperature, and curing duration, should also be investigated further. Additionally, the incorporation of lightweight aggregates or fibers may be explored to enhance specific panel properties. Upscaling to pilot-scale production and conducting life cycle assessments and cost-benefit analyses are also recommended to support the commercialization and broader adoption of this material.

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