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Effect of Liquid-To-Solid (L/S) Ratio on The Characteristics of Fly Ash and Pumice-Based Geopolymer Mortar for Lightweight Panel Applications

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Geopolymer Mortar; Fly Ash; Pumice; Liquid-To-Solid Ratio; Compressive Strength.

ABSTRACT
Fly ash and pumice-based geopolymers have emerged as promising low-carbon construction materials with the potential to reduce the environmental impacts associated with Portland cement production. However, their performance is highly dependent on mixture proportions, particularly the liquid-to-solid (L/S) ratio. Therefore, this study aimed to identify the optimum L/S ratio and evaluate its effect on the characteristics of fly ash and pumice-based geopolymer mortar. A laboratory experimental program was conducted using five liquid-to-solid (L/S) ratios of 0.40, 0.45, 0.50, 0.55, and 0.60. The investigated properties included compressive strength, density, and water absorption. The statistical significance of the L/S ratio was evaluated using one-way analysis of variance (ANOVA). The L/S ratio significantly influenced the compressive strength, density, and water absorption of geopolymer mortar. The optimum performance was achieved at an L/S ratio of 0.45, resulting in the highest compressive strength (21.03 MPa), highest density (2.12 g/cm³), and lowest water absorption (6%). One-way ANOVA confirmed that variations in the L/S ratio had statistically significant effects on all investigated properties ($p < 0.001$), with coefficients of determination of 99.44% for compressive strength, 98.42% for density, and 75.04% for water absorption. The liquid-to-solid (L/S) ratio was identified as a critical parameter governing matrix densification, porosity development, and the physical and mechanical properties of fly ash and pumice-based geopolymer mortar. An L/S ratio of 0.45 was recommended as the optimum condition for achieving the best balance among compressive strength, density, and water absorption.

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; Malhotra, 2010; Miller et al., 2018). Cement manufacturing generates substantial CO_2 emissions through limestone calcination and high thermal energy consumption during the production process. These environmental concerns have encouraged the development of more sustainable alternative materials, among which geopolymers have emerged as a promising solution. Geopolymers are aluminosilicate-based binder materials produced through reactions between precursor materials and alkaline activator solutions (Feng et al., 2024; Tomar et al., 2022). Compared with conventional Portland cement, geopolymers offer several advantages, including lower carbon emissions, superior chemical resistance, and the ability to utilize industrial by-products and natural resources as raw materials (Jwaida et al., 2023; Khasawneh, 2025; Mohan Kumar et al., 2025; Sambucci et al., 2021).

Fly ash is one of the most widely used precursor materials in geopolymer production due to its high silica and alumina contents (Dwibedy et al., 2024; Luhar & Luhar, 2022; Pedro et al., 2022; Xu et al., 2024). As the demand for sustainable construction materials continues to increase, research on geopolymers has expanded beyond improving mechanical performance toward the development of lightweight materials for panel and precast applications. Lightweight materials offer several advantages, including reduced structural dead loads, improved construction efficiency, and enhanced seismic performance. However, fly ash-based geopolymer mortar generally exhibits relatively high density, requiring the incorporation of lightweight materials to produce lighter construction products. One promising candidate is pumice, a porous volcanic rock characterized by low specific gravity and excellent thermal insulation properties. Indonesia, particularly Lombok Island, has abundant pumice deposits derived from the volcanic activity of Mount Rinjani. In addition to its lightweight characteristics, pumice contains significant amounts of silica and alumina that may contribute to the geopolymerization process. Therefore, incorporating pumice into geopolymer systems is attractive not only for reducing material density but also for promoting the utilization of locally available natural resources.

Despite these advantages, the incorporation of pumice may increase porosity and water absorption, which can adversely affect the mechanical performance of geopolymer materials. Consequently, optimizing mixture parameters is essential to achieve an appropriate balance among compressive strength, density, and water absorption. This study aimed to determine the optimum liquid-to-solid (L/S) ratio capable of producing the best balance among these properties in lightweight geopolymer mortar incorporating fly ash and locally sourced Lombok pumice. Furthermore, the significance of the L/S ratio on the characteristics of geopolymer mortar was evaluated using the inferential statistical approach of one-way analysis of variance (ANOVA).

Research on fly ash-based geopolymers has progressed considerably as part of efforts to develop low-carbon alternatives to Portland cement. Hardjito et al. (2004) demonstrated that mixture parameters, including NaOH molarity, the sodium silicate-to-sodium hydroxide ratio, and curing conditions, significantly influenced the compressive strength development of geopolymer materials. Similarly, Nath and Sarker (2014) reported that the incorporation of calcium-rich materials enhanced strength development under ambient curing conditions. These studies highlighted the critical role of mixture optimization and geopolymerization parameters in determining geopolymer performance.

The use of pumice as a geopolymer constituent has also attracted increasing attention due to its lightweight characteristics and aluminosilicate content. Hamid et al. (2022) reported that the combination of fly ash and pumice produced a denser and more homogeneous geopolymer matrix compared with pumice-based systems alone. Küçükyıldırım et al. (2023) demonstrated that alkaline activator composition directly influenced compressive strength development and geopolymer gel formation in pumice-based systems. Likewise, Karaaslan et al. (2022) found that incorporating calcium-rich materials improved matrix densification, reduced porosity, and enhanced the durability of pumice-based geopolymers.

In addition to material development, statistical approaches have increasingly been employed to better understand the relationships between mixture parameters and geopolymer performance. Quiatchon et al. (2021) applied Response Surface Methodology (RSM) and Analysis of Variance (ANOVA) to evaluate the influence of mixture parameters on the compressive strength of fly ash-based geopolymers. Similarly, Ekmen et al. (2022) reported that the liquid-to-binder ratio was among the most influential factors governing compressive strength, density, and water absorption in lightweight geopolymer materials incorporating fly ash and pumice aggregates. These findings suggested that liquid content plays a critical role in determining both the physical and mechanical properties of geopolymer materials.

Although fly ash–pumice-based geopolymers have demonstrated considerable potential as lightweight and sustainable construction materials, studies focusing on the optimization of the liquid-to-solid (L/S) ratio in systems incorporating fly ash and locally sourced pumice remain limited. Moreover, previous investigations have primarily relied on descriptive comparisons of experimental results without statistically evaluating the significance of mixture parameters on material characteristics. Therefore, this study aimed to determine the optimum L/S ratio and investigate its influence on the compressive strength, density, and water absorption of lightweight geopolymer mortar produced from fly ash and Lombok pumice using the inferential statistical method of one-way analysis of variance (ANOVA).

This research provides both theoretical and practical contributions. Theoretically, this study contributes to sustainable construction materials science by providing empirical evidence regarding L/S ratio optimization in fly ash and pumice-based geopolymers and expanding the literature on the application of ANOVA for evaluating the significance of mixture parameters. Furthermore, it highlights the potential of locally sourced Lombok pumice as an aluminosilicate material in geopolymer production. Practically, this research provides design guidelines for optimizing the L/S ratio in lightweight geopolymer mortar production, offering the construction industry an alternative material that reduces structural dead loads and improves construction efficiency. In addition, this study supports local resource utilization in Lombok through the application of abundant pumice deposits for value-added construction materials and serves as a statistical reference for future research on geopolymer mixture optimization.

METHOD

Materials

The materials used in this study consisted of fly ash, pumice, sand, sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3), and water. Fly ash was used as the primary precursor material in the geopolymer system, while pumice obtained from Lombok Island, West Nusa Tenggara, Indonesia, was incorporated as an additional aluminosilicate source and lightweight constituent. The alkaline activator solution was prepared using sodium hydroxide and sodium silicate to facilitate the geopolymerization process. Sand was used as the fine aggregate, while water was utilized for preparing the activator solution and supporting the mortar mixing process.

Methods

This study employed a laboratory experimental approach to evaluate the effect of the liquid-to-solid (L/S) ratio on the physical and mechanical properties of geopolymer mortar incorporating fly ash and pumice. The independent variable was the L/S ratio, which was evaluated at five levels: 0.40, 0.45, 0.50, 0.55, and 0.60. All other mixture parameters were maintained consistently to ensure that changes in material properties were attributed to variations in the L/S ratio.

The mortar preparation process began with the preparation of the alkaline activator solution by mixing sodium hydroxide and sodium silicate until a homogeneous solution was obtained. Subsequently, fly ash, pumice, and sand were dry-mixed using a laboratory mixer to achieve uniform distribution. The activator solution was gradually added to the mixture while mechanical mixing continued until a homogeneous geopolymer mortar was produced. The fresh mortar was cast into molds and compacted before being cured under predetermined conditions until the specified testing age.

The performance of the geopolymer mortar was evaluated through compressive strength, density, and water absorption tests. 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 geopolymer mortar.

RESULTS AND DISCUSSION

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

The experimental results demonstrated that the liquid-to-solid (L/S) ratio significantly influenced the compressive strength of fly ash–pumice-based geopolymer mortar. As illustrated in Figure 1, the compressive strength increased from 15.96 MPa at an L/S ratio of 0.40 to 21.03 MPa at an L/S ratio of 0.45. This 31.8% increase indicates that the addition of activator solution up to a certain level enhances the effectiveness of the geopolymerization process by promoting the dissolution of silica and alumina and accelerating geopolymer gel formation. Consequently, a denser and more homogeneous matrix is produced, resulting in improved load-bearing capacity. However, beyond the optimum ratio, compressive strength decreased progressively to 15.11 MPa, 10.25 MPa, and 8.91 MPa at L/S ratios of 0.50, 0.55, and 0.60, respectively. Compared with the optimum condition, the compressive strength at an L/S ratio of 0.60 decreased by approximately 57.6%, indicating that excessive liquid content adversely affects the mechanical performance of the geopolymer mortar.

The reduction in compressive strength at higher L/S ratios is likely associated with the increase in internal porosity resulting from excess liquid that does not fully participate in the geopolymerization process. During curing and hardening, part of the excess liquid evaporates and leaves voids within the matrix, producing a more porous and less compact microstructure. This condition weakens the bonding among aluminosilicate particles and reduces the material's resistance to compressive loading. These findings demonstrate that the L/S ratio plays a critical role in the development of fly ash–pumice-based geopolymer structures, with an L/S ratio of 0.45 representing the optimum condition for achieving the highest compressive strength and the most compact and stable geopolymer matrix.

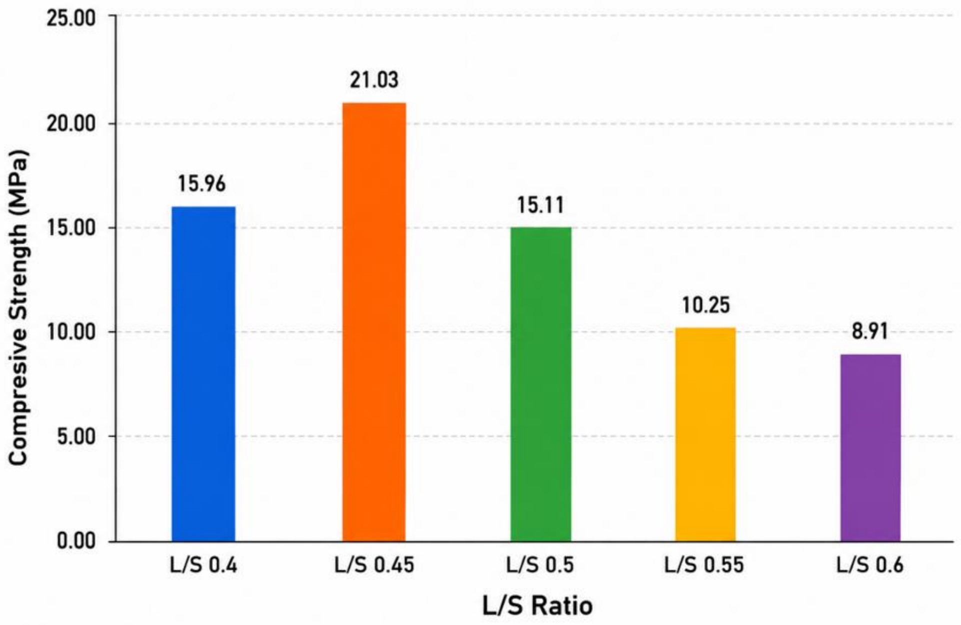

Figure 1. Effect of Liquid-to-Solid (L/S) Ratio on the Compressive Strength of Fly Ash–Pumice-Based Geopolymer Mortar

Source: Laboratory test results, 2026

The results presented in Figure 2 indicate that the liquid-to-solid (L/S) ratio significantly influenced the density of fly ash–pumice-based geopolymer mortar. The density increased from 1.96 g/cm³ at an L/S ratio of 0.40 to 2.12 g/cm³ at an L/S ratio of 0.45, which represented the highest value among all mixture variations. This increase suggests that the addition of activator solution up to a certain level improved the mixing process and promoted a more uniform distribution of the activator within the geopolymer system, resulting in a denser and more homogeneous matrix. However, when the L/S ratio exceeded 0.45, the density gradually decreased to 1.76 g/cm³, 1.69 g/cm³, and 1.58 g/cm³ at L/S ratios of 0.50, 0.55, and 0.60, respectively. These results indicate that excessive liquid content adversely affects the compactness of the hardened geopolymer matrix.

The observed density trend demonstrates the critical role of the L/S ratio in controlling matrix densification. At low to optimum L/S ratios, the amount of activator solution is sufficient to facilitate geopolymerization and promote the formation of a compact internal structure. In contrast, higher L/S ratios introduce excess liquid that may evaporate during curing, leaving additional voids within the matrix and consequently increasing porosity while reducing density. This behavior is consistent with the compressive strength results, where the mixture exhibiting the highest density at an L/S ratio of 0.45 also achieved the highest compressive strength of 21.03 MPa. These findings suggest that improved matrix densification contributes directly to enhanced microstructural quality and mechanical performance of fly ash–pumice-based geopolymer mortar.

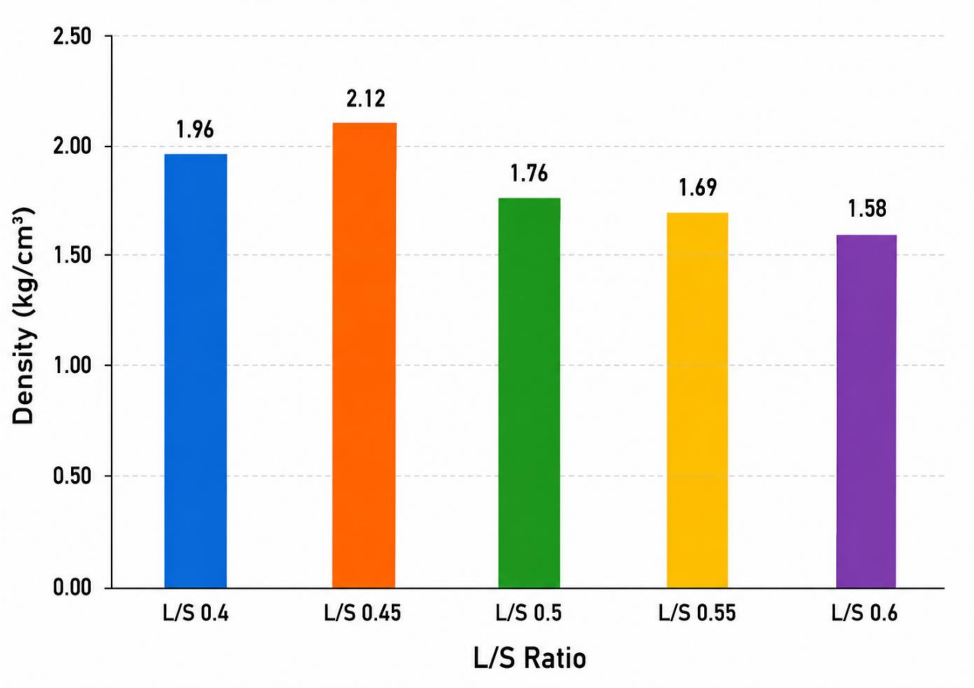

Figure 2. Effect of Liquid-to-Solid (L/S) Ratio on the Density of Fly Ash–Pumice-Based Geopolymer Mortar

Source: Laboratory test results, 2026

The results presented in Figure 3 indicate that the liquid-to-solid (L/S) ratio had a significant influence on the water absorption behavior of fly ash–pumice-based geopolymer mortar. The lowest water absorption value was obtained at an L/S ratio of 0.45 (6%), whereas the highest value was recorded at an L/S ratio of 0.60 (13%). In general, increasing the L/S ratio beyond the optimum level resulted in a progressive increase in water absorption. At an L/S ratio of 0.40, water absorption was measured at 7% and decreased to 6% at an L/S ratio of 0.45. However, as the L/S ratio increased to 0.50, 0.55, and 0.60, the water absorption values gradually increased to 8%, 10%, and 13%, respectively. These results indicate that the liquid content of the mixture directly affects the ability of the geopolymer mortar to absorb water.

The reduced water absorption observed at an L/S ratio of 0.45 suggests the formation of a denser and more homogeneous geopolymer matrix with fewer interconnected pores available for water penetration. This observation is consistent with the compressive strength and density results, where the optimum L/S ratio of 0.45 produced the highest compressive strength (21.03 MPa) and the highest density (2.12 g/cm^3). In contrast, increasing the L/S ratio beyond the optimum level promoted greater porosity due to excess liquid that did not fully participate in the geopolymerization process and subsequently left voids after curing. As a result, water absorption increased while matrix compactness decreased. These findings confirm that an L/S ratio of 0.45 represents the optimum condition for achieving the most favorable combination of high compressive strength, high density, and low water absorption in fly ash–pumice-based geopolymer mortar.

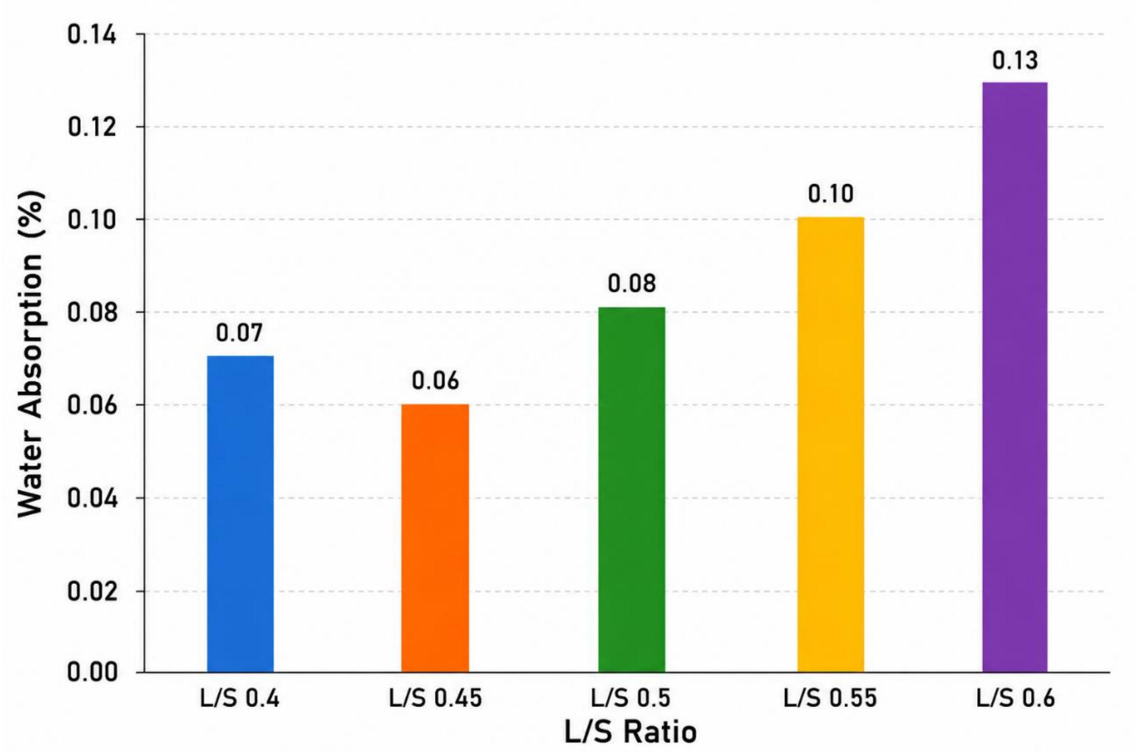

Figure 3. Effect of Liquid-to-Solid (L/S) Ratio on the Water Absorption of Fly Ash–Pumice-Based Geopolymer Mortar
Source: Laboratory test results, 2026

Overall, the results demonstrate that the liquid-to-solid (L/S) ratio exerts a consistent influence on the compressive strength, density, and water absorption of fly ash–pumice-based geopolymer mortar. These properties exhibited a strong interrelationship, whereby higher compressive strength was generally associated with increased density and reduced water absorption. Conversely, lower compressive strength was accompanied by decreased density and increased water absorption. This relationship indicates that variations in the L/S ratio directly affect matrix densification and internal porosity, which ultimately govern the overall quality and performance of the geopolymer mortar.

The results showed that increasing the L/S ratio from 0.40 to 0.45 enhanced the compressive strength from 15.96 MPa to 21.03 MPa and increased the density from 1.96 g/cm^3 to 2.12 g/cm^3, while reducing water absorption from 7% to 6%. However, further increases in the L/S ratio beyond the optimum level resulted in significant reductions in compressive strength and density, accompanied by a progressive increase in water absorption, reaching 13% at an L/S ratio of 0.60. These trends suggest that matrix densification is closely related to both the mechanical and physical performance of the material. A denser matrix generally produces higher compressive strength and lower water absorption, whereas increased porosity leads to reduced strength and greater susceptibility to water ingress.

These findings are consistent with those reported by Hardjito et al. (2004), who identified liquid content as one of the key factors governing compressive strength development in geopolymer systems. Insufficient liquid content may limit the dissolution of aluminosilicate precursors, whereas excessive liquid tends to increase internal porosity and reduce material strength. Similar observations were reported by Quiatchon et al. (2021), who demonstrated that the activator-to-fly ash ratio significantly influences geopolymer strength development and exhibits an optimum level beyond which performance declines due to excess liquid within the system. Furthermore, Ekmen et al. (2022) reported that the liquid-to-binder ratio is among the dominant parameters controlling density, compressive strength, and water absorption in lightweight geopolymers incorporating fly ash and pumice aggregates. Therefore, the present study confirms that optimizing the L/S ratio is essential for producing fly ash–pumice-based geopolymer mortar with superior mechanical performance, adequate density, and low water absorption through the formation of a denser and more homogeneous geopolymer matrix.

Statistical Analysis Using One-Way ANOVA

The one-way ANOVA results presented in Figure 4 indicate that the liquid-to-solid (L/S) ratio had a highly significant effect on the compressive strength of fly ash–pumice-based geopolymer mortar. An F-value of 890.01 with a p-value of 0.000 demonstrates that the observed differences in compressive strength among the tested mixtures were not caused by random variation but were significantly influenced by changes in the liquid content of the mixture. The coefficient of determination (R^2) reached 99.44%, supported by an adjusted R^2 (R^2adj) of 99.33% and a predicted R^2 (R^2pred) of 99.13%, indicating that nearly all variations in compressive strength could be explained by changes in the L/S ratio. The highest average compressive strength was obtained at an L/S ratio of 0.45 (21.03 MPa), whereas the lowest value was recorded at an L/S ratio of 0.60 (8.91 MPa).

The results of Tukey's post-hoc test revealed that all L/S ratio levels belonged to statistically distinct groups, indicating that each variation produced a significantly different compressive strength response. These findings further support the descriptive analysis, confirming that the L/S ratio is a critical parameter governing the mechanical performance of geopolymer mortar. Increasing the L/S ratio up to 0.45 enhanced the effectiveness of the geopolymerization process and promoted the formation of a denser matrix structure. In contrast, excessive liquid content increased internal porosity through the formation of voids during curing, thereby reducing the material's ability to withstand compressive loading. Therefore, an L/S ratio of 0.45 can be identified as the optimum condition for achieving the highest mechanical performance in fly ash–pumice-based geopolymer mortar.

These findings suggest that the compressive strength of fly ash–pumice-based geopolymer mortar is strongly governed by the balance between geopolymerization efficiency and porosity development. Within the investigated range, an L/S ratio of 0.45 provided sufficient activator solution to promote precursor dissolution and geopolymer gel formation without generating excessive free liquid. In contrast, higher L/S ratios increased the likelihood of pore formation due to liquid evaporation during curing, resulting in a less compact matrix and lower compressive strength. This behavior confirms that optimizing the L/S ratio is essential for achieving a dense and mechanically stable geopolymer structure.

WORKSHEET 1

One-way ANOVA: L/S 0.4; L/S 0.45; L/S 0.5; L/S 0.55; L/S 0.6

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 0.4; L/S 0.45; L/S 0.5; L/S 0.55; L/S 0.6

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	4	470,520	117,630	890,01	0,000
Error	20	2,643	0,132		
Total	24	473,164			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,363549	99,44%	99,33%	99,13%

Means

Factor	N	Mean	StDev	95% CI
L/S 0.4	5	15,957	0,435	(15,618; 16,296)
L/S 0.45	5	21,028	0,336	(20,688; 21,367)
L/S 0.5	5	15,108	0,468	(14,769; 15,447)
L/S 0.55	5	10,253	0,308	(9,914; 10,592)
L/S 0.6	5	8,9072	0,2098	(8,5681; 9,2464)

Pooled StDev = 0.363549

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping				
L/S 0.45	5	21,028	A				
L/S 0.4	5	15,957		B			
L/S 0.5	5	15,108			C		
L/S 0.55	5	10,253				D	
L/S 0.6	5	8,9072					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 Fly Ash–Pumice-Based Geopolymer Mortar

Source: Statistical analysis using SPSS, 2026

The one-way ANOVA results presented in Figure 5 indicate that the liquid-to-solid (L/S) ratio had a highly significant effect on the density of fly ash–pumice-based geopolymer mortar. An F-value of 311.16 with a p-value of 0.000 confirms that the differences in density observed among the tested mixtures were significantly influenced by variations in the liquid content of the mixture. The statistical model exhibited an excellent goodness-of-fit, with an R^2 value of 98.42%, an adjusted R^2 (R^2adj) of 98.10%, and a predicted R^2 (R^2pred) of 97.53%. These results indicate that most of the variation in density can be explained by changes in the L/S ratio. The highest average density was obtained at an L/S ratio of 0.45 (2.1173 g/cm³), whereas the lowest value was recorded at an L/S ratio of 0.60 (1.5836 g/cm³).

WORKSHEET 1

One-way ANOVA: L/S 0.4; L/S 0.45; L/S 0.5; L/S 0.55; L/S 0.6

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 0.4; L/S 0.45; L/S 0.5; L/S 0.55; L/S 0.6

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	4	0,91496	0,228740	311,16	0,000
Error	20	0,01470	0,000735		
Total	24	0,92966			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,0271129	98,42%	98,10%	97,53%

Means

Factor	N	Mean	StDev	95% CI
L/S 0.4	5	1,9558	0,0292	(1,9305; 1,9811)
L/S 0.45	5	2,1173	0,0313	(2,0921; 2,1426)
L/S 0.5	5	1,7578	0,0253	(1,7325; 1,7831)
L/S 0.55	5	1,6920	0,0278	(1,6667; 1,7173)
L/S 0.6	5	1,58358	0,02071	(1,55828; 1,60887)

Pooled StDev = 0,0271129

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
L/S 0.45	5	2,1173	A
L/S 0.4	5	1,9558	B
L/S 0.5	5	1,7578	C
L/S 0.55	5	1,6920	D
L/S 0.6	5	1,58358	E

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 Fly Ash–Pumice-Based Geopolymer Mortar

Source: Statistical analysis using SPSS, 2026

The results of Tukey's post-hoc test revealed that all L/S ratio levels belonged to statistically distinct groups, indicating that each variation produced a significant difference in density. These findings reinforce the descriptive results, confirming that the L/S ratio plays a crucial role in controlling the densification of the geopolymer matrix. Increasing the L/S ratio up to 0.45 improved activator distribution and promoted the formation of a denser and more homogeneous structure. In contrast, excessive liquid content increased porosity through the formation of internal voids during the hardening process, resulting in a significant reduction in material density at higher L/S ratios. Therefore, an L/S ratio of 0.45 can be regarded as the optimum condition for achieving the highest degree of matrix densification in fly ash–pumice-based geopolymer mortar.

The one-way ANOVA results presented in Figure 6 indicate that the liquid-to-solid (L/S) ratio had a significant effect on the water absorption of fly ash–pumice-based geopolymer mortar. An F-value of 15.03 with a p-value of 0.000 confirms that the observed differences in water absorption among the tested mixtures were significantly influenced by variations in the liquid content of the mixture. The statistical model exhibited a satisfactory level of fit, with an R^2 value of 75.04%, an adjusted R^2 (R^2adj) of 70.05%, and a predicted R^2 (R^2pred) of 61.00%. These results indicate that a substantial proportion of the variation in water absorption can be explained by changes in the L/S ratio, although additional factors not included in the model may also contribute to the water absorption behavior of the material. The lowest water absorption value was obtained at an L/S ratio of 0.45 (5.63%), whereas the highest value was recorded at an L/S ratio of 0.60 (12.63%).

The results of Tukey's post-hoc test revealed partial overlap among several L/S ratio groups, indicating that the differences in water absorption were less pronounced than those observed for compressive strength and density. Nevertheless, statistically significant differences were still identified between mixtures with low and high L/S ratios. These findings support the descriptive analysis, confirming that increasing the L/S ratio generally increases the water absorption capacity of the material due to the development of greater internal porosity during curing. Excess liquid that does not fully participate in the geopolymerization process may leave voids within the hardened matrix, creating additional pathways for water penetration. Therefore, an L/S ratio of 0.45 can be regarded as the optimum condition for minimizing water absorption, indicating the formation of a denser geopolymer structure with lower porosity compared with the other mixture variations.

These findings suggest that water absorption is closely related to the pore structure developed during geopolymerization. Within the investigated range, an L/S ratio of 0.45 provided sufficient liquid to facilitate geopolymer gel formation while minimizing the formation of excess voids. In contrast, higher L/S ratios increased the amount of free liquid within the mixture, which subsequently evaporated during curing and generated additional capillary pores. As a result, the hardened geopolymer matrix became more permeable to water ingress, leading to higher water absorption values. This behavior confirms that controlling the L/S ratio is essential for reducing porosity and improving the durability-related properties of fly ash–pumice-based geopolymer mortar.

WORKSHEET 1

One-way ANOVA: L/S 0.4; L/S 0.45; L/S 0.5; L/S 0.55; L/S 0.6

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 0.4; L/S 0.45; L/S 0.5; L/S 0.55; L/S 0.6

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	4	0,015351	0,003838	15,03	0,000
Error	20	0,005105	0,000255		
Total	24	0,020456			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,0159770	75,04%	70,05%	61,00%

Means

Factor	N	Mean	StDev	95% CI
L/S 0.4	5	0,06530	0,00929	(0,05039; 0,08020)
L/S 0.45	5	0,05633	0,01583	(0,04143; 0,07123)
L/S 0.5	5	0,08059	0,00966	(0,06568; 0,09549)
L/S 0.55	5	0,0965	0,0254	(0,0816; 0,1114)
L/S 0.6	5	0,12633	0,01426	(0,11143; 0,14124)

Pooled StDev = 0,0159770

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping		
L/S 0.6	5	0,12633	A		
L/S 0.55	5	0,0965	A	B	
L/S 0.5	5	0,08059		B	C
L/S 0.4	5	0,06530			C
L/S 0.45	5	0,05633			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 Fly Ash–Pumice-Based Geopolymer Mortar

Source: Statistical analysis using SPSS, 2026

Overall, the statistical analysis demonstrated that the liquid-to-solid (L/S) ratio had a significant effect on all investigated characteristics of fly ash–pumice-based geopolymer mortar, namely compressive strength, density, and water absorption. The p-value of 0.000 obtained for all three parameters confirms that the observed variations in material properties were not random but were significantly influenced by changes in the liquid content of the geopolymer system. Furthermore, the high coefficients of determination for compressive strength (R^2 = 99.44%) and density (R^2 = 98.42%) indicate that the L/S ratio is the dominant factor governing the mechanical and physical performance of the material. Although the coefficient of determination for water absorption was comparatively lower (R^2 = 75.04%), the results still demonstrate a substantial contribution of the L/S ratio to the water absorption behavior of the geopolymer mortar.

The statistical results further revealed that an L/S ratio of 0.45 produced the most favorable combination of properties among all investigated mixtures, yielding the highest compressive strength (21.03 MPa), highest density (2.1173 g/cm^3), and lowest water absorption (5.63%). In contrast, increasing the L/S ratio to 0.60 reduced the compressive strength to 8.91 MPa and the density to 1.5836 g/cm^3, while increasing water absorption to 12.63%. These trends indicate that increasing the liquid content up to an optimum level enhances precursor dissolution and geopolymer gel formation, thereby improving matrix densification. However, excessive liquid promotes the formation of internal voids that increase porosity, resulting in reduced matrix density, lower compressive strength, and greater susceptibility to water penetration.

These findings are consistent with those reported by Hardjito et al. (2004), who identified liquid content as one of the primary factors governing compressive strength development in geopolymer systems. Similar observations were reported by Quiatchon et al. (2021), who demonstrated that the activator-to-fly ash ratio exhibits an optimum level beyond which performance declines due to increased porosity. Furthermore, Ekmen et al. (2022) reported that the liquid-to-binder ratio is a critical parameter controlling the relationship among density, compressive strength, and water absorption in lightweight geopolymers incorporating fly ash and pumice aggregates. Therefore, the statistical analysis not only validates the experimental observations but also confirms that optimizing the L/S ratio is essential for producing fly ash–pumice-based geopolymer mortar with a denser matrix, higher compressive strength, and lower water absorption.

CONCLUSION

This study was conducted to determine the optimum liquid-to-solid (L/S) ratio and evaluate the significance of its effect on the characteristics of lightweight geopolymer mortar incorporating fly ash and pumice. Based on the findings, the following conclusions were drawn. First, the descriptive analysis demonstrated that the L/S ratio significantly influenced the compressive strength, density, and water absorption of geopolymer mortar. Increasing the L/S ratio from 0.40 to 0.45 improved the compressive strength from 15.96 MPa to 21.03 MPa and increased the density from 1.96 g/cm^3 to 2.12 g/cm^3, while reducing water absorption from 7% to 6%. However, further increases in the L/S ratio beyond 0.45 resulted in lower compressive strength and density, accompanied by higher water absorption. These results indicated that an L/S ratio of 0.45 represented the optimum condition, producing the highest compressive strength and density while achieving the lowest water absorption. The findings suggested that an optimum L/S ratio promoted the formation of a denser and more homogeneous geopolymer matrix with reduced porosity.

Second, inferential statistical 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. The p-value of <0.001 obtained for compressive strength, density, and water absorption indicated that the observed variations in material characteristics were significantly associated with changes in the L/S ratio. These findings were further supported by the high coefficients of determination, reaching 99.44% for compressive strength, 98.42% for density, and 75.04% for water absorption. Therefore, the L/S ratio was identified as a key parameter governing the performance of fly ash–pumice-based geopolymer mortar, with an optimum value of 0.45 providing the most favorable balance between mechanical and physical properties.

Based on the findings and limitations of this study, several recommendations are proposed for future research. Further studies should evaluate additional mechanical properties, such as flexural and tensile strength, as well as durability aspects, including chemical resistance, freeze–thaw cycles, and thermal stability. The effects of other parameters, including alkaline activator concentration, curing temperature, curing duration, and aging period, should also be investigated. The incorporation of fibers or other lightweight aggregates may be explored to enhance specific panel properties. Pilot-scale production and life cycle assessment (LCA) are recommended to evaluate the economic feasibility and environmental benefits of this material for commercial applications. Comparative studies involving other precursor materials and statistical optimization approaches, such as response surface methodology (RSM), are also suggested to develop more comprehensive predictive models for geopolymer mixture design.

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