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Effect of Alkaline Activator Composition and Curing Regimes on the Properties of Pumice-Based Geopolymer Mortars

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Abstract

The current study explores the effects of alkaline activator composition and curing regimes on the properties of geopolymer mortars synthesized primarily from pumice dust. Three sodium silicate-to-sodium hydroxide (SS/SH) ratios (2.5, 2.0, and 1.5) and two NaOH molarities (10M and 12M) were the variables to design six mixtures. Specimens were treated under three curing regimes: C1 (80 °C for 2 days), C2 (80 °C for 3 days), and C3 (hybrid regime: 80 °C for 2 days followed by 160 °C for 1 day). The six mixtures were evaluated based on flowability, compressive strength, dry density, water absorption, and visual efflorescence. Results revealed that flowability increased with the decrease in the SS/SH ratio and molarity. The increase in the SS/SH ratio increased compressive strength. The highest compressive strength was recorded in curing (C1) at SS/SH of 2.5 and the molarity of 10, indicating that higher molarity does not always lead to higher compressive strength. Prolonged curing duration decreased compressive strength. Hybrid curing (C3) caused 12M mixes to have the highest strength, unlike the curing regime (C1), where 10M mixes were the highest. Moreover, mixes with SS/SH of 1.5 and 2 at 12M achieved their highest strength values in the hybrid regime (C3). The decrease in the SS/SH ratio and molarity decreased the density and increased the absorption. The extended curing regime (C2) or the hybrid regime (C3) increased density and reduced absorption, but did not necessarily increase compressive strength in most cases. The decrease in the SS/SH ratio increased efflorescence, but the extension of curing duration mitigated it. The highest recorded compressive strength of 37.2 MPa was achieved at 10 M and SS/SH = 2.5 under curing 1 (C1), accompanied by a water absorption of 12.7%.

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Highlights:

- Study investigates geopolymer mortars from pumice dust with varying activators.
- Six mixtures tested with different SS/SH ratios and NaOH molarities.
- Curing regimes included three methods affecting flowability and strength.
- Higher SS/SH ratios improved compressive strength; prolonged curing reduced it.
- Lower ratios increased efflorescence, but longer curing durations reduced it.

1. Introduction

The production and use of concrete have many negative impacts on the environment, including the excessive consumption of energy and natural resources to produce cement, the main material in concrete production. According to one study, concrete is regarded as the world's second most widely used material, and its production leads to degradation in the environment, including the release of greenhouse gases [1], depletion of natural resources [2], and pollution. These issues associated with concrete make it necessary to move toward more environmentally friendly products. A more sustainable replacement for cement, because it generates a lower carbon footprint, is geopolymer, an aluminosilicate-based binder synthesized by the alkali activators.

Intensive research has been conducted in the last few years on geopolymer to better understand the relationship between mechanical properties and the ratio between sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH), along with the NaOH molarity, and the curing conditions. Much of the existing research has concentrated on precursors, such as fly ash, slag, and metakaolin. Limited research was conducted on a geopolymer synthesized using pumice dust. Moreover, in most studies on a geopolymer synthesized using pumice dust, the pumice dust was not the primary precursor; it was used as an addictive. There is a variation in the results of geopolymers produced using pumice dust. Some studies have found that the performance of the geopolymer is weak and suitable only for nonstructural applications [3][4], while other research has reported compressive strengths exceeding 70 MPa [5,6]. Pumice is a volcanic material that is available in many places in Saudi Arabia, and it can be utilized as a precursor for geopolymer production because it contains a high amount of amorphous silica and alumina. Valle et al. used pumice stone and silica fume as precursors for geopolymer production at SS/SH of 2.5 and molarity of 8 and 12 at a curing temperature of 60 °C for 120 hours. The highest compressive strength achieved was 14.1 MPa when the molarity was 12 [5]. Oti et al. used pumice powder to produce geopolymer at a molarity of 10, and the compressive strength of 18.8 MPa was achieved in 28 days [3]. Zeyad et al. produced geopolymer mortars using volcanic pumice powder at SS/SH of 2.5 and molarity of 10 under curing conditions of 65 °C for 1 day. The compressive strength and density obtained on the 28th day were 23.5 MPa and 2165 kg/m^3, respectively [7]. The effects of curing temperature (ambient, 60 °C, 75 °C, 90 °C, and 105 °C) and duration (4 hours to 168 hours) on properties of pumice-based geopolymer in the presence of fly ash (30%) were investigated at SS/SH of 2 [5]. The results showed that a peak compressive strength of 82.8 MPa occurred when the specimens were cured at 75 °C for 168 hours. The density and absorption at the same curing condition were 2000 kg/m^3 and 5.5%, respectively. Moreover, compressive strength was reduced when the duration of elevated curing temperatures of 90 °C and 105 °C exceeded 24 hours. Properties of pumice-based geopolymer pastes were investigated with variations in molarity (8 to 18M), curing temperature (ambient, 60, 80, and 100 °C), and duration (24, 48, 72, and 120 hours) at SS/SH of 2.5 [6]. The findings exhibited that the maximum compressive strength was about 76 MPa when the curing temperature was 60°C for 120 days at a molarity of 12. When molarity exceeded 12M or when the curing temperature was elevated (100 °C), the compressive strength decreased. In geopolymer, there are two types of gels: low calcium gels and high calcium gels. The two mentioned gels often exist in hybrid systems. In geopolymers with limited calcium, sodium aluminosilicate hydrate (N-A-S-H) gels constitute the dominant amorphous binder; in contrast, systems rich in calcium mainly produce calcium aluminosilicate hydrate (C-A-S-H) gels. For low-calcium aluminosilicate precursors, a reactive SiO_2/Al_2O_3 molar ratio above about 1.5 is generally required to obtain N–A–S–H-type gels [8]. Pumice dust, when it is used as a primary binder, N A S H gels would be the primary amorphous binding phase since pumice is low in calcium. A kind of activator and curing temperature influence reaction kinetics. Curing temperature and duration also affect the production of N A S H gels in the geopolymerization process [9,10]. The extension of curing duration results in silica-rich products, which promote the strength development of the geopolymer. Additionally, binders are not the only source of silica that forms a part of N A S H gels, but also the sodium silicate activator may contribute to forming N A S H gels [11,12]. Gel structures of N A S H are influenced by polymerization degree in sodium silicate, which is directly proportional to its SiO_2/Na_2O ratio. Studies demonstrate that a SiO_2/Al_2O_3 ratio ranging from 2.0 to 12.3 is advantageous for obtaining high compressive strength in geopolymer binders[13,14]. The mechanical performance of pumice-based geopolymer is critically affected by the Na_2SiO_3-to-NaOH (SS/SH) ratio, the concentration (molarity) of the NaOH solution, and the applied curing temperature and duration. Much research has shown that higher molarity with an optimal SS/SH ratio enhances geopolymerization, resulting in improved strength and microstructure [15,16], while curing conditions such as elevated temperatures or prolonged curing optimize strength gain. However, excessive molarity or curing temperatures may result in strength loss or decreased durability [16,17].

This study aims to determine the optimal sodium silicate/sodium hydroxide (SS/SH) ratio, NaOH molarity, and curing regime for achieving enhanced mechanical and durability performance in pumice-based geopolymer mortars. Pumice dust was selected as the sole binder due to its abundance and cost-effectiveness in Saudi Arabia. This study explores the effects of SS/SH ratio, NaOH molarity, and curing regime on the performance of pumice-based geopolymer mortar. The key properties evaluated in this study were flowability, compressive strength, dry density, water absorption, and efflorescence, to determine the optimal conditions for producing durable, high-performance pumice-based geopolymer mortar. Although several studies have investigated geopolymers derived from fly ash or slag, limited studies have focused on pumice-based systems. The combined influence of alkaline activator composition and curing regimes on the mechanical and durability-related characteristics of pumice-based geopolymers remains insufficiently understood. Therefore, this study aims to bridge that gap.

2. Materials and Methods

2.1. Materials

The sole binder used in this research was pumice dust, a natural aluminosilicate substance that is known for its pozzolanic reactivity. The pumice dust in this study was collected from Jazan, Saudi Arabia. The pumice dust was ground using a ball mill to make it very fine, which led to increased surface area, prompting reactions. The specific gravity of the pumice was 2.6, while the average particle size was around 15 µm. The chemical composition of pumice dust is shown in

Table **1.** Oxide composition of pumice dust.

. All pumice dust used in this study was obtained from a single, uniform batch with consistent chemical and physical properties to ensure minimal variability and reliable reproducibility of the results. Based on the oxide composition of pumice dust, the SiO_2 and Al_2O_3 contents (43.7% and 17.56%, respectively) provide a solid aluminosilicate base, yielding a SiO_2/Al_2O_3 molar ratio of approximately 2.1, which falls at the lower limit of the optimal geopolymerization range (2.0–3.0). This ratio enables effective N–A–S–H gel formation, but at a lower level than with higher-silica precursors [18,19]. The percentage of CaO is almost 10%, which is considered low, but it can lead to faster setting times and improve early compressive strength. The alkaline activator solution was prepared using sodium hydroxide (NaOH) flakes at two molarity levels: 12M and 10M. The other activator was sodium silicate (Na_2SiO_3) solution. The two activators were mixed at ratios of sodium silicate to sodium hydroxide (SS/SH) equal to 2.5, 2, and 1.5 by mass to prepare the geopolymer mortar mixtures. The 10M and 12M NaOH solutions exhibited relatively low viscosities, approximately 10–12 mPa·s and 18–22 mPa·s at 25 °C, respectively. In contrast, the sodium silicate solution had a significantly higher viscosity of about 158 mPa·s at 27 °C, reflecting its higher dissolved solids content and silicate polymerization. The fine aggregate was added to the mixtures at a constant fine aggregate-to-binder ratio of 1.5.

Oxide (%)	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	K_2O	SO_3
Pumice Dust	43.7	17.56	9.99	9.69	7.45	4.92	1.94	0.08

Table 1. *Oxide composition of pumice dust.*

2.2. Mix design and specimen preparation

Six pumice-based geopolymer mortar mixtures were designed in this study with specific variations in the sodium silicate to sodium hydroxide (SS/SH) ratio and molarity of NaOH, as shown in **Error! Reference source not found.**. The selected variants aim to investigate their impact on the mortar's properties, enabling a comprehensive analysis of how different activator compositions influence the geopolymerization process. A constant activator/binder ratio of 0.35 and a fine-aggregate/binder ratio of 1.5 were used throughout the study to ensure consistency across the mixtures. The NaOH solution was prepared by dissolving 98.52%-pure sodium hydroxide flakes in distilled water. It was then allowed to cool for 24 hours until it reached room temperature before being combined with the sodium silicate solution. The dry materials (pumice dust and fine aggregate) were mixed first, then the two activators (Na_2SiO_3 and NaOH) were added gradually to the dry materials, ensuring a controlled and homogeneous incorporation of the liquid components. The freshly prepared mortar was cast into $50 \times 50 \times 50\,mm^3$ molds and was left in the lab for about one hour before moving the molds to the oven for curing, where specific temperature conditions were applied to promote geopolymerization. This experimental arrangement facilitated a comprehensive assessment of the impact of variations in activator composition and curing regime on the efficacy of pumice-based geopolymer mortars, providing significant insights to support the creation of environmentally sustainable construction materials.

Table 2. *Geopolymer mortar mix design matrix*

Mix	Molarity	Na_2SiO_3/ NaOH	Activators/ binder	Fine aggregate/ binder
1	12	2.5	0.35	1.5
2	12	2	0.35	1.5
3	12	1.5	0.35	1.5
4	10	2.5	0.35	1.5
5	10	2	0.35	1.5
6	10	1.5	0.35	1.5

2.3. Curing regimes and testing methods

Three distinct curing regimes were employed in this study to investigate how they affected the characteristics of the pumice-based geopolymer mortars. The first regime, C1, involved oven curing at 80°C for two days, while the second, C2, extended the same temperature treatment to three days. The third regime, C3, was a hybrid approach, combining oven curing at 80°C for two days followed by an additional day at 160°C. The hybrid curing regime (C3) was selected to combine the benefits of moderate and high temperatures. The initial stage at 80 °C promotes controlled dissolution and early geopolymer network formation, while the brief exposure to 160 °C accelerates further polycondensation and densification. These curing methods were developed with the intention of investigating the possible changes in the performance of geopolymer mortar under a variety of curing conditions. The fresh property of flowability was assessed immediately after mixing using the flow table test, as outlined in ASTM C1437, to evaluate the mixtures' workability. All hardened properties, including compressive strength, density, and water absorption, were measured at 28 days of age to ensure consistency in evaluating the long-term effects of the curing regimes. Compressive strength was tested in accordance with ASTM C109, providing insights into the geopolymer mortars' structural integrity. Density and water absorption were determined following ASTM C642, offering data on the mortars' compactness and permeability. Moreover, visual inspections were conducted in order to assess efflorescence, a potential surface defect, in each of the three different curing regimes (C1, C2, and C3). These inspections helped identify any aesthetic or durability issues resulting from the curing processes. This comprehensive approach ensured a thorough understanding of how curing conditions influence the performance of pumice-derived geopolymer mortars in their fresh and hardened conditions, which contributed valuable insights to material science and engineering applications. **Error! Reference source**

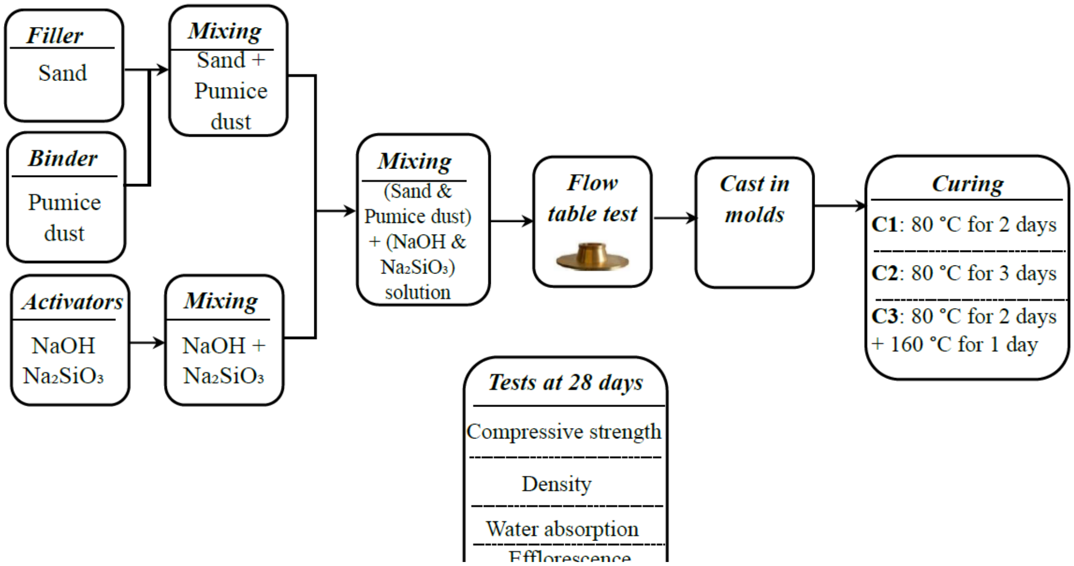

Figure 1. *Graphical depiction of the experimental procedure.*

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3. Results and Discussion

The analysis of the experimental results obtained for the geopolymer mortar mixes under different conditions is presented in this section. The discussion focuses on characteristics, which consisted of flowability, compressive strength, density, and water absorption, and the visual assessment of efflorescence. The variables in this study are the SS/SH ratio (2.5, 2, and 1.5), NaOH molarity (12M and 10M), and curing condition (80 °C for 2 days, 80 °C for 3 days, and 80 °C for 2 days followed by 160 °C for 1 day). The goal is to gain insights into the optimal mix design and curing conditions for enhanced performance.

3.1. Flowability

The flow diameters for all pumice-based geopolymer mortars are exhibited in **Error! Reference source not found.**. The flowability of the geopolymer mortars was strongly affected by both the sodium silicate–sodium hydroxide ratio (SS/SH) and the concentration (molarity) of the NaOH solution. For a molarity of 12, the flow diameters of the mixtures were 23.5, 25.8, and 28 cm for SS/SH equal to 2.5, 2, and 1.5, respectively. For a molarity of 10, the diameters of the mixtures were 28.3, >30, and >30 cm for SS/SH equal to 2.5, 2, and 1.5, respectively. Clearly, the flow diameter increased as the SS/SH ratio decreased from 2.5 to 1.5, indicating an improvement in workability. This improvement in workability, once the SS/SH ratio decreases, is attributed to the lower viscosity of sodium hydroxide to sodium silicate solution, since higher viscosity (as higher SS/SH) restricted geopolymer mortar flow [20]. Similar to the effect of reducing the SS/SH ratio, the decrease in molarity led to improvement in flowability among all SS/SH ratios. The increase in molarity of NaOH reduced the flowability of geopolymer mortar due to the higher viscosity and increased cohesiveness of the solution, which led to a stiffer mix [21,22]. Therefore, the highest workability was observed in the mix with SS/SH=1.5 and 10M, while the lowest workability was seen in the mix with SS/SH=2.5 and 12M. Flow diameters were generally high, and the flow of two mixtures exceeded the flow table limit because the pumice dust contained only about 10% of calcium oxide (CaO), which, at a higher percentage, can accelerate the setting time and reduce workability [23].

3.2. Compressive strength

Compressive strength results showed a complex interaction between SS/SH ratio, molarity, and curing regime. For curing regime one (C1), compressive strength values achieved in this curing regime were the highest among the three curing regimes. As shown in **Error! Reference source not found.**, comparing 12M to 10M, mixtures with 10M yielded the highest compressive strength. The highest strength values for 12M and 10M were 33.8 MPa and 37.2 MPa, respectively, at an SS/SH ratio of 2.5, while the lowest strength values for 12M and 10M were 21.4 MPa and 28.4 MPa, respectively, at an SS/SH ratio of 1.5. These differences are explained by the balance between aluminosilicate dissolution and polycondensation: at 10M, dissolution proceeds at a controlled pace, allowing uniform gel formation and a stable N–A–S–H network, whereas 12M produces excessively high alkalinity, rapid dissolution, high viscosity, and incomplete gel development. This trend aligns with established alkali-activation chemistry, where very high molarity accelerates dissolution but can disrupt gel formation [8,19].

Higher SS/SH ratios provided more soluble silicate, improving strength up to an optimal range of 2.0–2.5. Beyond this level, the mixture became overly viscous and less homogeneous, reducing strength. The optimal point depends on precursor reactivity: low-reactivity materials such as pumice reach this limit earlier, whereas fly ash or metakaolin can tolerate higher silicate contents, and slag-based systems typically require much lower ratios.

For curing C2, the increase in the duration of curing from 2 days to 3 days led to a reduction in compressive strength in all mixtures. For instance, extending the curing time to three days at 80 °C reduced the strength of the mix with an SS/SH ratio of 2.5 and 12M from 33.8 MPa to 22.2 MPa, whereas the mix with the same SS/SH ratio but 10M experienced a decrease from 37.2 MPa to 29.7 MPa. The decrease in strength of the mix with SS/SH of 1.5 and 10M was most pronounced in this curing regime. This strength loss is consistent with reported behavior where prolonged high-temperature curing increases porosity, promotes microdefects, and ultimately leads to a coarser microstructure and reduced reaction progress [24,25].

For hybrid curing C3, 80 °C for 2 days followed by 160 °C for 1 day, increasing the curing temperature to 160 °C helped partially restore strength, particularly for the 12M mixes. The mixes with SS/SH ratios of 2 and 1.5 and 12M had compressive strength higher than those in C1 and C2. Moreover, in C1 and C2, 10M mixes demonstrated superior compressive strength when compared with 12M mixes; however, in C3, 12M mixes achieved their peak compressive strength as a result of their stronger alkaline environment, which facilitates more complete dissolution of aluminosilicates and formation of a denser N-A-S-H gel network. Compared to curing C2, all mixtures in C3 exhibited compressive strength higher than that of curing C2. Although prolonging curing to 3 days at 80 °C reduced strength, raising the curing temperature to 160 °C promoted further geopolymerization and densification by accelerating the dissolution of unreacted particles, resulting in higher strength.

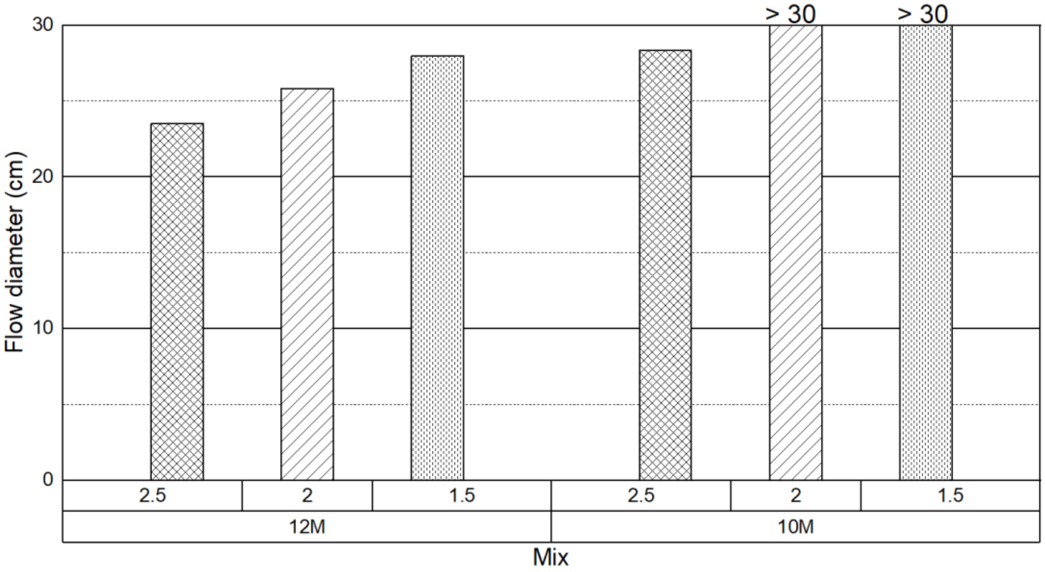

Figure 2. *Flow diameters for all mixes.*

Compared C3 to C1, the mixes with SS/SH values of 2 and 1.5 at 12M were the only mixtures exhibiting higher strength. The observed enhancement in compressive strength can be explained by the balance between alkali activation kinetics and the silicate content. At 12M concentration, high temperature exposure enhances the polymerization rate and may promote crystallization or consolidation of aluminosilicate gels, practically in low-silicate systems (SS/SH = 1.5 and 2), which had not yet fully reacted in C1. Mixes with SS/SH of 2.5 were already rich in silicate and likely experienced gel formation near complete during C1. Therefore, additional heat in C3 may have caused structural instability, gel shrinkage, or microcracking, leading to no improvement or even slight strength loss. The finding in C3 shows that the benefit of hybrid curing is most pronounced in mixes that were under-reacted in C1 but not overly dried in C2.

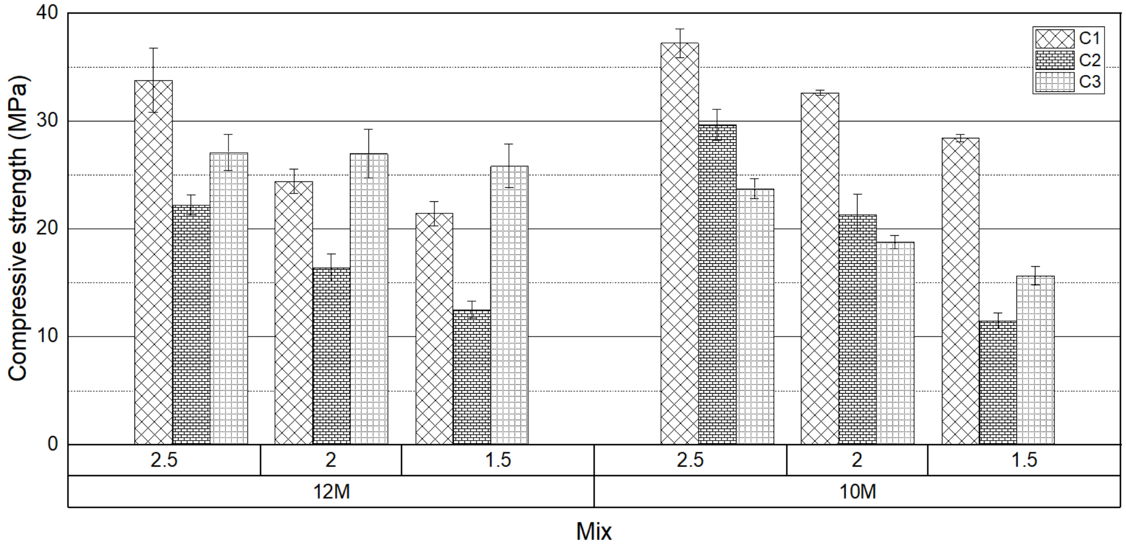

Figure 3. *Compressive strength at the three curing regimes.*

The low calcium content of pumice (~10% CaO) means the system forms slow-developing N–A–S–H gels rather than the faster C–A–S–H gels typical in slag. As a result, early-age strength is lower, but with optimized curing, especially hybrid C3, adequate strength can still be achieved. Although crystallinity was not experimentally examined in this study, recent research has shown that higher curing temperatures and temperature gradients similar to those used in C3 can promote partial crystallization or structural reorganization within aluminosilicate gels [26,27]. This may help explain the improved strength observed under hybrid curing and highlights an important direction for future microstructural work. The findings are generally consistent with studies from Turkey, where pumice-based geopolymers cured at 60–105 °C for up to 168 hours have reported strengths as high as 76 MPa. In our study, strengths did not exceed 37.2 MPa, which is likely related to variations in the chemical composition and reactivity of the pumice utilized in each region [5,6].

3.3. Density

presents the density values for all mortars at different curing regimes. The increase in the SS/SH ratio increased density. For example, at 12M in C1, the density increased from 1911 kg/m^3 to 1994 kg/m^3 as the SS/SH ratio was raised from 1.5 to 2.5. The SS/SH ratio influenced the density mainly through the amount of silicate available for gel formation. A higher silicate content facilitated a denser matrix formation by producing more sodium aluminosilicate hydrate (N-A-S-H) gels that filled voids more effectively. However, excessive sodium silicate (higher viscosity) makes the formation of polymer gels more difficult, resulting in a less dense matrix [28]. Also, the increase in molarity increased the density. For example, at SS/SH of 2.5 in C1, the density rosed from 1944 kg/m^3 at 10M to 1994 kg/m^3 at 12M. This increase in density is because adding solute particles to a specific mass of solvent elevates the total mass of the solution without substantially changing its volume, frequently resulting in a greater proportional rise in mass than in volume [29,30].

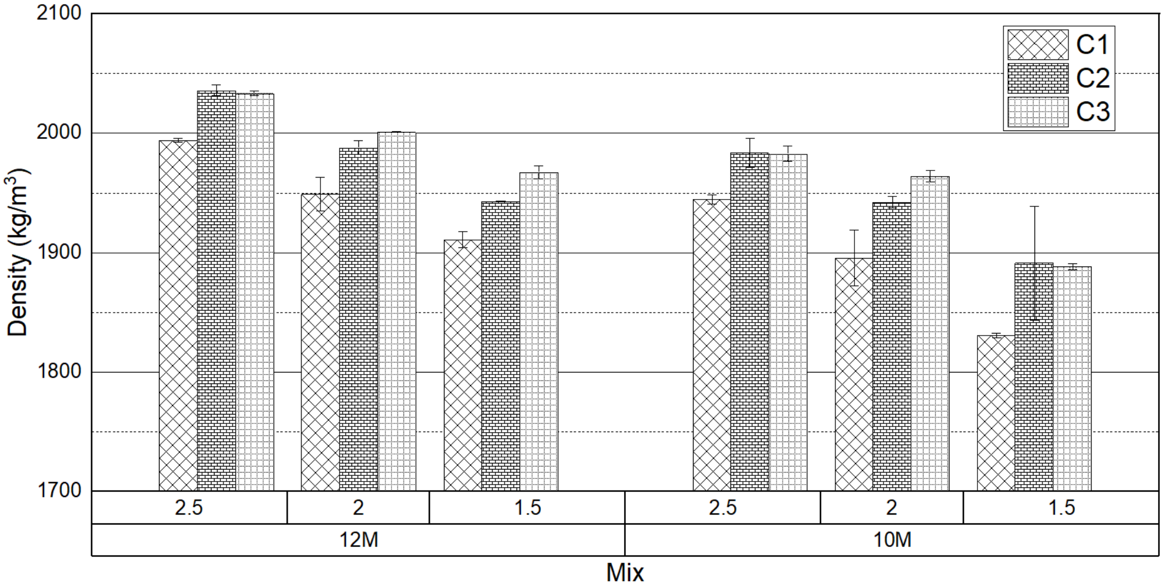

Figure 4. *Density for all geopolymer mortars at different regimes.*

Regarding curing regime, the density of the pumice-based geopolymer mortars generally increased with the curing duration and elevated curing temperature, indicating better compaction and a more consolidated microstructure. For all mixtures, the density in C2 slightly increased compared to C1, indicating progressive geopolymerization. For instance, the density increased from 1994 kg/m^3 in C1 to 2036 kg/m^3 in C2 at 12M and SS/SH of 2.5. There was no direct correlation between density and compressive strength. Higher density did not always translate to higher strength. In C2, density increased compared to C1, while strength declined, likely due to microcracking. In hybrid curing (C3), the density continued to rise in most cases or stabilized. For example, at 12M and SS/SH of a 2.5, the mixture reached the highest recorded density of 2036 kg/m³ in C2, while the same mixture showed a density of 2033 kg/m³ in C3, indicating that prolonged moderate curing and short-term high-temperature exposure both promoted densification. The increase in density is ascribed to the fact that the hybrid curing regime (C3 80°C for 2 days followed by 160°C for 1 day) enhanced geopolymerization by combining moderate-temperature dissolution with high-temperature gel consolidation, resulting in a denser and more compact N–A–S–H network and reducing porosity in comparison with constant temperature curing. Although microstructural analysis was not performed in this study, previous research has shown that stepped or elevated thermal curing accelerates dissolution of aluminosilicate, reduces microcracking, and improves overall gel continuity and strength [19,26].

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3.4. Water absorption

Raising the SS/SH ratio led to a notable reduction in absorption for the same molarity and curing conditions, as shown in **Error! Reference source not found.**. For example, absorption decreased from 13.6% to 10% when the SS/SH values rose from 1.5 to 2.5 at a molarity of 12 in curing (C1). This reduction in absorption as the SS/SH ratio was raised is attributed to the greater availability of soluble silicate at higher SS/SH ratios, which promoted the formation of a more continuous and refined N-A-S-H gel network, effectively filling pores and reducing capillary pathways. A pattern similar to that observed for the SS/SH ratio was also evident with the NaOH molarity. When the molarity of the alkaline solution increased, the absorption values dropped even when the mixes had the same SS/SH ratio and were exposed to identical curing conditions. This suggests that stronger alkaline environments promote more effective dissolution and reaction of the precursor materials, leading to a denser internal structure that is less capable of absorbing water. For instance, the absorption value dropped from 12.7% to 10% when the molarity increased from 10M to 12M for an SS/SH of 2.5 in C1. This drop in absorption when molarity increased indicates that a stronger concentration of alkali facilitates precursor dissolution and gel formation, hence decreasing porosity.

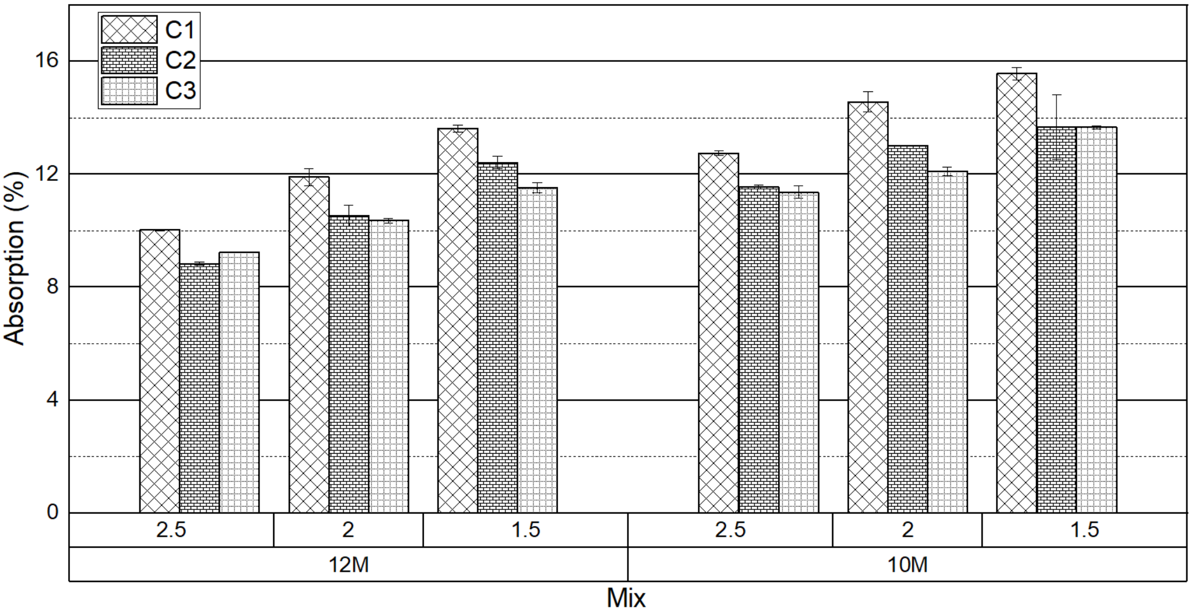

Figure 5. Absorption (%) for all mixes.

In terms of curing regime, the highest absorption values were observed in curing (C1). The mix with SS/SH of 1.5 at 10M exhibited the highest absorption of 15.6% since it had the lowest SS/SH ratio (1.5) and molarity (10M). The prolongation of curing at the same temperature (C2) decreased absorption. For example, the absorption decreased from 10% in C1 to 8.8% in C2 for the mix with SS/SH of 2.5 and 12M because of improved gel maturation and matrix densification when curing was prolonged. The hybrid curing regime (C3) also reduced absorption in most mixes.

3.5. Correlation between compressive strength and water absorption

Error! Reference source not found. exhibits the relationship between compressive strength and water absorption for different mixes and curing regimes. Obviously, there is an inverse relationship between compressive strength and water absorption among all curing conditions. For the same molarity and curing conditions, a mix with the lowest absorption had the highest compressive strength. For example, in curing (C1) and 12M, a mix with absorption of 10% had a compressive strength of 33.8 MPa, while a mix with absorption of 13.6% had a compressive strength of 24.4 MPa. However, it is not a rule that the lowest absorption leads to the highest strength. The mix with SS/SH of 2.5 and 10M achieved the highest strength (37.2 MPa), although it had a higher absorption (12.7%) than its 12M counterpart (33.8 MPa and 10% absorption). At 12M, excessive NaOH may have accelerated aluminosilicate dissolution beyond the optimal rate for polycondensation, leading to microstructural defects and a weaker binder matrix. In contrast, at 10M, the system likely enabled a better balance between dissolution and gelation, favoring the development of a denser, more mechanically stable geopolymer network despite greater capillary porosity indicated by higher absorption.

In the prolonged curing regime (C2), all mixtures exhibited a notable strength reduction, although absorption values decreased for all mixtures. For example, at 10M and SS/SH of 1.5, the strength decreased from 28.4 MPa at C1 to 11.5 MPa at C2, although the highest reduction in absorption took place in the same mix when absorption dropped from 15.6% to 13.7%. The reason for this observation is more likely due to the prolonged heat exposure, which likely led to matrix degradation (microcracks, shrinkage), while low silicate and low alkalinity limited gel development. However, the result was a denser, mechanically weaker geopolymer, hence lower strength despite lower absorption.

In the hybrid curing regime (C3), at 12M, mixes with SS/SH ratios of 2 and 1.5 yielded the highest compressive strength (27 and 25.8 MPa) in all curing regimes, while absorption dropped 10.4% and 11.5%, respectively. This observation supports the idea that optimal strength in geopolymer mortars is a result of carefully balanced chemistry and curing, where a moderate molarity (like 10M) may outperform a higher one under short heat exposure but become less resilient under extended or elevated temperatures. Compared to C2, the strength in all mixes in C3 partially recovered, while absorption decreased except for the mix with 12M and SS/SH of 2.5, which increased.

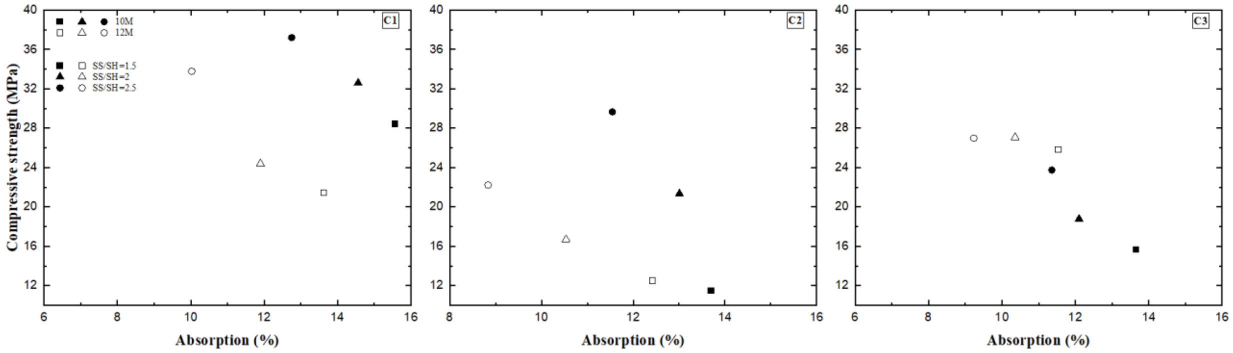

Figure 6. Compressive strength vs. absorption for different mixes and curing regimes

3.6. Visual assessment of efflorescence

Error! Reference source not found. exhibits geopolymer mortar specimens under varying curing regimes at the age of 28 days. For curing (C1), efflorescence is obvious in most specimens, as seen in the pictures. The efflorescence became more noticeable as the SS/SH ratio was lowered because a lower SS/SH ratio often leads to a higher concentration of soluble salt, sodium hydroxide, which are prone to leaching out and reacting with carbon dioxide in the atmosphere to form efflorescence on the surface of the specimen. The specimens with a high SS/SH ratio of 2.5 showed minimal or no visible efflorescence, indicating effective geopolymerization and alkali binding, which was reflected by their compressive strength. Higher molarity (12M) seems to form more efflorescence, as can be seen when comparing the two mixes with SS/SH of 2 at 12M and 10M. A higher molarity means a higher concentration of salt, NaOH, migrating to the surface of the specimens during drying and crystallizing, causing efflorescence. Efflorescence can affect aesthetic appearance and slightly weaken the outer layer through alkali migration. However, it has minimal influence on the bulk mechanical performance of the mortar. Alkali movement toward the surface may locally increase porosity and reduce surface integrity, but this effect remains shallow and does not compromise overall strength. In future mix designs, the incorporation of fine supplementary materials like fly ash or silica fume could help further mitigate efflorescence by refining the pore structure and binding excess alkalis. For curing (C2) and (C3), extension of curing at 80 °C or rising curing temperature to 160 °C mitigated efflorescence by allowing more complete geopolymerization and reducing free alkalis in the system.

4. Conclusion

The impacts of SS/SH ratios (2.5, 2, and 1.5), molarity of NaOH (12M and 10M), and curing regimes (C1, C2, and C3) on the performance of pumice dust-based geopolymer mortars were investigated in this study. The results in this experimental study demonstrate that:

- Flowability improved with the decrease of the SS/SH ratio and molarity due to reduced viscosity and increased water content, but excessive flow was observed in some mixes, exceeding the flow table limits.
- Compressive strength was enhanced with the increase in the SS/SH ratio and molarity. In curing (C1), the highest compressive strength was observed when the molarity was 10, proving that it is not always the case that higher molarity leads to higher compressive strength. In curing (C2), all mixes exhibited a

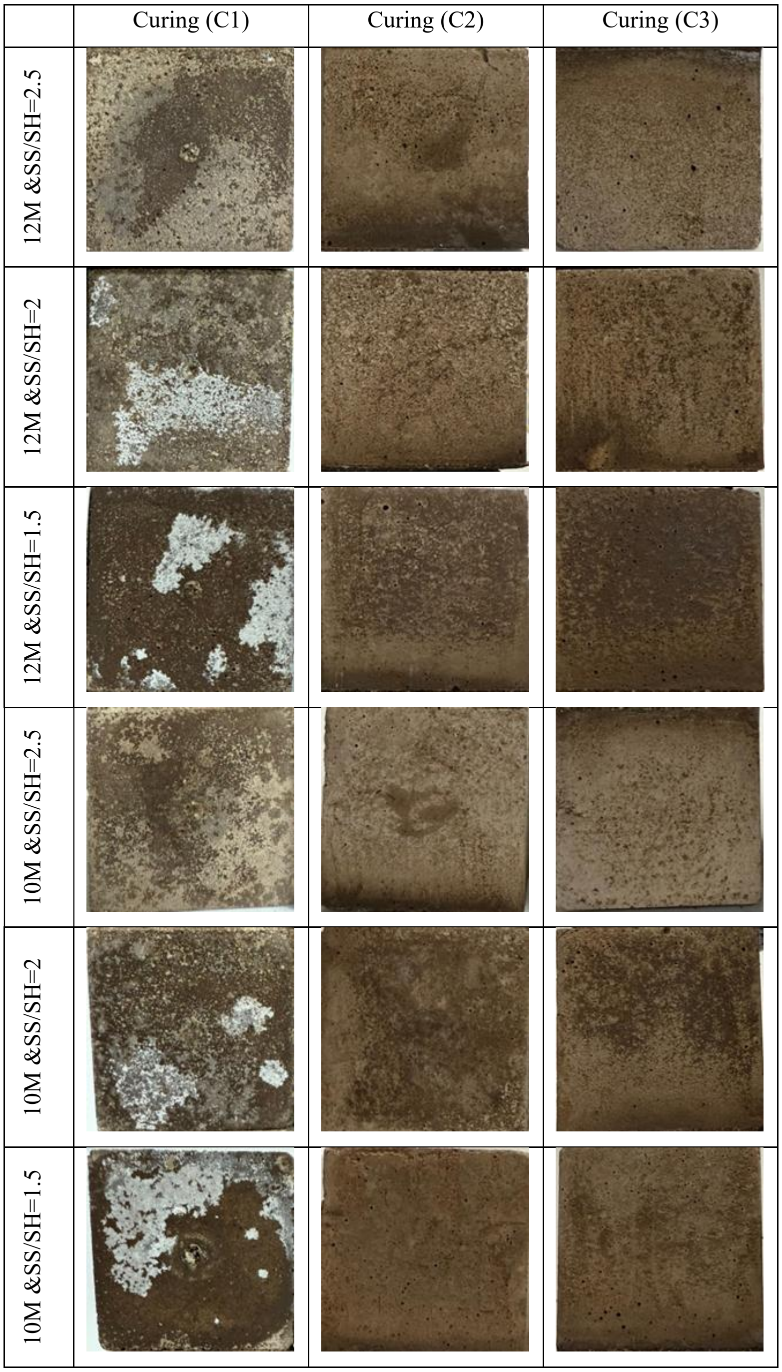

Figure 7. *Specimen under varying curing regimes.*

reduction in their strength. In curing (C3), all mixes with 12M had an improvement in strength compared to C2. The highest compressive strength in this curing regime (C3) was observed when the molarity was 12. Moreover, two mixes with 12M reached their highest strength in this curing regime (C3). The increase in strength in this regime was due to additional geopolymerization and densification caused by the dissolution of unreacted particles.

- Density decreased with a decrease in the SS/SH ratio or molarity. Although the density in C1 for 10M was less than that for 12M, the compressive strength for mixes with 10M was higher than that for 12M. Mixes in both curing regimes (C2 and C3) exhibited lower density compared to that in the curing regime (C1) due to extended curing duration.

- Water absorption decreased with the increase in SS/SH ratio or molarity. Water absorption had an inverse relationship with compressive strength. Higher absorption led to lower compressive strength. For the curing regime (C1), absorption for 10M mixes was higher than that for 12M mixes, but the compressive strength for the 10M mixes was higher. For curing regimes (C2 and C3), all mixtures exhibited less absorption compared to that of C1.
- Visual inspection confirmed that higher alkali contents and lower silicate ratios increased efflorescence under short curing, while prolonged curing suppressed it.
- SS/SH ratios between 2.0 and 2.5 provide the optimal balance of workability and strength.

Overall, the optimum performance for curing was observed in mixes with 10M. Extension of curing duration led to strength degradation. For optimal performance in hybrid curing (C3), moderate SS/SH ratios (1.5 to 2.0) combined with high molarity (12M) cured is recommended. Optimized pumice-based geopolymer mixes achieved structural-grade strengths (>37 MPa), demonstrating their suitability for structural applications. However, prolonged curing at constant temperature should be avoided, and optimized regimes such as C3 are recommended for reliable performance.

This study has several limitations. Microstructural analyses such as SEM, XRD, or FTIR were not performed, which restricts the ability to directly verify gel formation or link curing conditions to specific microstructural changes. In addition, only elevated-temperature curing was investigated, and long-term durability aspects such as chemical attack and shrinkage were not evaluated. These limitations highlight important opportunities for future research to build on the findings of this study.

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