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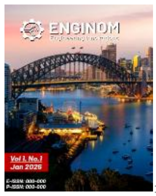

Investigations on the Behavior of Alum-slag and Albite Based Geopolymer Mortar in Relation to the Type of Alkaline Solution

Article,

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Abstract

An experimental investigation on the efficient use of Albite and aluminum slag in geopolymer mortar is presented in this publication. For varying mix proportions, alkaline activators based on sodium were combined with sodium meta silicate (Na_2SiO_3). The Na_2SiO_3/NaOH ratio and the molarity of the NaOH solution served as the study's parameters. Three concentrations of NaOH (8, 12, and 16 molars) were examined. The findings demonstrated that the factors under investigation had a major impact on the characteristics of the geopolymer mortars that were created. The accelerated mortar bar test (AMBT), workability, setting time, and pozzolanic activity were examined and reported.

Keywords: Albite; Aluminum slag; Pozzolanic activity; Geopolymer mortar; Alkaline- Activators; Alkali-aggregate reaction.

1. Introduction

An alumino-silicate material (such as metakaolin, fly ash, natural Albite, pozzolan, etc.) in an alkaline solution produces a unique class of three-dimensional inorganic polymers called geopolymers [1], [2], [3]. Sialate (O-Si-O-Al-O), the basic monomer unit, is composed of alternating tetrahedral SiO_4 and AlO_4 joined by sharing all of the oxygen [4]. Furthermore, silicon and aluminum from geological sources as well as industrial wastes like FA (Class F, low calcium) make up the majority of geopolymer, an inorganic alumino-hydroxide polymer [5], [6]. In the present circumstances, replacing the cement only partially is insufficient [7], [8]. The development of a cement alternative with a less environmental impact is necessary [9]. The term "geopolymer" was first used by Ahmed et al. [10]and [11] to describe alumino-silicate binders, which are produced by alkali activation of a parent material with a high silicon and aluminum content. The remarkable properties of these binders promote their usage as materials to replace cement [8], [12]. Geo-polymerization is based on the alumino-silica chain [13]. A polymeric reaction between a certain amount of silica and alumina takes place in the presence of a strong alkaline solution (NaOH, KOH, etc.) [14]. Alkali activation, another name for geo-polymerization, modifies the amorphous components [4], [15], [16].

Despite our incomplete understanding, the three main stages of the geo-polymerization process are the condensation of precursor ions into monomers, the polymerization of monomers into three-dimensional polymeric structures, and the dissolution of Si and Al species present in the raw materials due to the influence of hydroxide ions [17], [18], [19]. These three activities might happen simultaneously or in tandem with each other [20], [21], [22]. Water is formed as a discontinuous, hole-free paste during the polymerization process [23], [24], [25]. Water does not participate in the chemical reaction; it merely provides the geopolymer with workability and an initial reaction media [26].

When OPC structures contain reactive aggregates (including amorphous or weakly crystalline silica), an unfavorable reaction known as the alkali-aggregate reaction (AAR) occurs if the alkali concentration is too high [27], [28], [29]. The danger of AAR-related damage must be assessed because geopolymers are alkali-activated materials [3], [30]. The alkali-aggregate reaction in OPC is assessed using the accelerated test, ASTM C1260 [31], which entails curing mortar samples at 80° C in 1 M NaOH. Supplemental cementitious materials (SCM) like fly ash, blast-furnace slag, and silica fume are commonly thought of as a mitigating method against the growth of ASR in concrete [5], [6], [32]. However, how well an SCM lowers the ASR depends on its type, dosage, and type of reactive aggregate [12], [33]. The effectiveness of an SCM is determined by its alkali content; more alkali concentration leads to greater expansion [23], [34], [35]. The expansion of mortar specimens containing reactive aggregates was reduced when fly ash was substituted for portion of the cement [16], [36]. Fly ash can significantly reduce the alkalinity of the pore solution, which lowers the ASR [22], [37].

1.1. Research Significance

The present research is of significant scientific and practical importance as it investigates the behavior of alum-slag and albite based geopolymer mortar in relation to the type of alkaline solution, which is a critical factor governing geo-polymerization kinetics, microstructural development, and final engineering performance. Geopolymer materials are increasingly recognized as sustainable alternatives to conventional Portland cement due to their lower carbon footprint, superior durability, and ability to utilize industrial by-products such as slag and aluminosilicate minerals.

The type and concentration of the alkaline activator directly influence the dissolution of silica and alumina species, gel formation, setting characteristics, strength development, and long-term durability of the mortar matrix. In particular, the incorporation of albite as a reactive aluminosilicate mineral offers promising potential for improving dimensional stability, microstructural densification, and chemical resistance. Recent studies have confirmed that alkaline solution chemistry plays a decisive role in controlling geopolymer reaction mechanisms and hardened properties. Therefore, this study contributes to the development of optimized and environmentally friendly construction materials by identifying the most effective alkaline solution type for enhancing the mechanical and durability performance of geopolymer mortars. The findings are expected to provide valuable guidance for the design of high-performance sustainable binders suitable for structural and infrastructure applications, while also supporting global efforts toward reducing CO_2 emissions associated with traditional cement-based materials.

2. Materials and Methods

2.1. Subsection

2.1.1. Alum-Slag

The specific gravity of alum-slag (water-cooled aluminum slag) is 2.65 g/cm^3, its volumetric weight is 1.18 g/cm3, its specific surface area is 5200 cm^2/gm, and its soundness is 1.12 mm. Alum-slag's particle size distribution is shown in Figure 1. It is a dark gray color. The physical properties of the two constituent materials are as follows. Albite has a specific gravity of 2.18 g/cm^3, a specific surface area of 6180 cm^2/g, a soundness of 1.04 mm, and a white color.

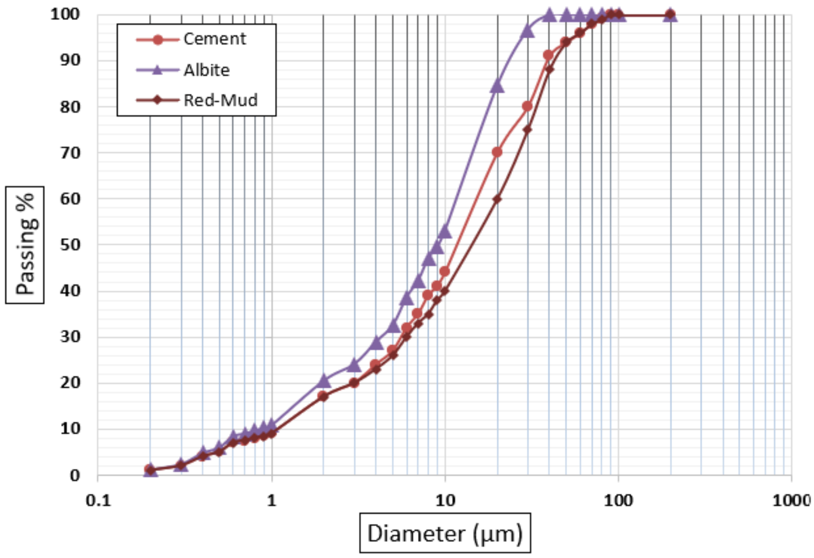

Figure 1. This is a figure. Schemes follow the same formatting.

Table 1. Chemical composition of constituent Albite and Alum-slag

Oxides	Na_2O	MgO	Al_2O_3	P_2O_5	SO_3	Cl	K_2O	CaO	Fe_2O_3	LOI
Albite	0.67	0.02	12.14	0.09	0.57	Nil	3.21	5.1	4.06	10.2
Alum-slag	0.65	2.27	56.8	0.45	1.18	0.8	0.61	6.18	2.99	0.79

2.1.2. Albite

Alum-slag, or water-cooled aluminum slag, has a specific gravity of 2.65 g/cm³, a volumetric weight of 1.18 g/cm³, a specific surface area of 5200 cm²/gm, and a soundness of 1.12 mm. Figure 1 displays the particle size distribution of alum-slag. It is a deep shade of gray. Alum-slag's physical properties (according to reference [10]) exhibit a higher specific gravity of 2.65 g/cm³, a specific surface area of 5200 cm²/g, a soundness of 1.12 mm, and a dark-grey color.

2.1.3. FA, OPC and Fine aggregate

The binder used was ordinary Portland cement (grade CEM 42.5 N), exhibiting a specific surface area of 3000 cm²/g and a specific gravity of 3.13 g/cm³. The fly ash (FA) employed in this study was procured from Sika Egypt for Construction Chemicals. According to ASTM C618-12a, fly ash falls into two categories: Class C (high-calcium, CaO > 10%) and Class F (low-calcium, CaO < 10%). The present investigation adopted low-calcium FA. Its chemical composition is provided in Table 2. As for the fine aggregate, natural siliceous sand was selected, characterized by a specific gravity of 2.54 g/cm³, a fineness modulus of 2.60, and a bulk density of 1.81 g/cm³.

Table 2. Chemical composition of constituent OPC and fly ash

Oxides	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	SO_3	Fe_2O_3	LOI
OPC	0.29	1.24	5.48	20.29	0.17	0.45	63.11	2.49	2.85	3.39
Fly ash	0.43	1.1	27.28	54.72	1.12	1	5.31	1.01	5.15	6.8

2.1.4. Materials/Solution for Activators

Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) were the alkaline activators utilized. Solution of sodium meta-silicate ($Na_2SiO_3 \cdot 9H_2O$) (Na = 16.17%, O_2 = 67.55%, H_2 = 6.38%, and Si = 9.88% by mass). Melting point: 1.088 °C; density: 2.4 g/cm^3. It is 98% pure, crystalline, and has a molecular weight (M.W.) of 284.2 g/mole. Glass water with a high specific gravity is another name for sodium meta-silicate. Sodium hydroxide (NaOH) has a molecular weight (M.W.) of 40 g/mole, a density of 2.13 g/cm^3, a melting point of 318 °C, and 96% purity.

2.2. Specimen Preparation and Curing

2.2.1. Material preparation

Albite and alum-slag as raw ingredients was selected. using a Retsch grinder to get a particle size that passes a # 200 ASTM sieve (75 µm) of alum-slag and Albite.

2.2.2. Solution for Activators

As an alkaline activator, sodium hydroxide or potassium hydroxide solution was combined with sodium meta-silicate (glass water). The molarity of the NaOH solution and the [Na_2SiO_3/NaOH] ratio were the parameters used in this investigation. Three concentrations of NaOH (8, 12, and 16 molarity (M)) were examined. A step of 0.5 was used to vary the Na_2SiO_3/NaOH ratio between 1 and 2.5.

2.2.3. Fresh mortar and casting

All mortar mixtures were prepared using a binder-to-sand ratio of 1:3, where the binder consisted either of cement, low-calcium fly ash (LCFA), Albite, or Alum-slag. A fixed alkali solution-to-binder ratio of 0.55 was adopted across all mixes. The complete mix compositions are presented in Table 3, organized into two phases. The mixing protocol strictly followed the procedure outlined in ASTM C305 [38] for ordinary Portland cement mortars. Prismatic mortar bar specimens measuring 25 × 25 × 285 mm were also cast. These bars were initially cured for 24 hours at ambient temperature under a relative humidity of no less than 95%. Subsequently, the mortar bars were immersed for 24 hours in a 1 M NaOH solution preheated to 80 °C. Following this preconditioning step, the initial length of each bar was recorded as the zero reading. The specimens were then kept continuously in the same 1 M NaOH solution at 80 °C for an additional 14 days, in full accordance with ASTM C1260 [31] before subsequent measurements were taken.

Related to Table 3, the table presents the mix design parameters and material proportions for a series of control and geopolymer mortar mixtures, where NaOH solution is used as the alkaline activator. The columns detail the quantities (in grams) of each constituent, including Ordinary Portland Cement (OPC) for conventional mixes, Low-Calcium Fly Ash (LCFA), Albite, and Alum-slag as alternative aluminosilicate precursors, along with a constant sand content of 600 g across all mixtures to maintain comparable aggregate proportions. The alkaline activation system is defined through varying concentrations of sodium hydroxide (NaOH) solutions (8 M, 12 M, and 16 M), combined with corresponding amounts of sodium silicate (Na_2SiO_3) solution, where the ratio between Na_2SiO_3 and NaOH is systematically adjusted (e.g., 1, 1.5, 2, and 2.5) to study its influence on geo-polymerization. The table includes control mixes such as C-M (pure OPC) and LCFA-M (partial replacement with fly ash), followed by geopolymer mixes categorized into two main groups: A-series (Albite-based) and AS-series (Alum-slag-based). Within each group, mixtures are further differentiated by NaOH molarity and Na_2SiO_3/NaOH ratio, reflected in the mix designations (e.g., A-8Na-1, AS-12Na-2.5). The binder content is typically fixed at 200 g for geopolymer mixes (either albite or alum-slag), ensuring consistency in comparison. Additionally, the water-to-binder ratio

(W/B) is maintained at 0.55 for selected mixes, indicating controlled workability conditions. Overall, the table is structured to systematically investigate the effects of precursor type, alkaline solution concentration, and activator ratio on the performance of geopolymer mortars, enabling a comprehensive analysis of mechanical and durability properties under controlled compositional variations.

Table 3. Mix parameters and proportions of the FA based geopolymer, with NaOH as alkaline activator

Mix. Designation	OPC	LCFA	Albite	Alum-slag	Sand	NaOH Solution (g)			Na_2SiO_3	W/B
	(g)	(g)	(g)	(g)	(g)	8 M	12 M	16 M	Solution (g)	
C-M	200	–	—	—	600	—	—	—	—	0.55
LCFA-M	140	60	—	—	600	—	—	—	—	
A -8Na-1	—	—	200	—	600	55	—	—	55	
A -8Na-1.5	—	—	200	—	600	44	—	—	66	
A -8Na-2	—	—	200	—	600	36.7	—	—	73.3	
A -8Na-2.5	—	—	200	—	600	31.4	—	—	78.6	
A -12Na-1	—	—	200	—	600	—	55	—	55	
A -12Na-1.5	—	—	200	—	600	—	44	—	66	
A-12Na-2	—	—	200	—	600	—	36.7	—	73.3	0.55
A -12Na-2.5	—	—	200	—	600	—	31.4	—	78.6	
A -16Na-1	—	—	200	—	600	—	—	55	55	
A -16Na-1.5	—	—	200	—	600	—	—	44	66	
A -16Na-2	—	—	200	—	600	—	—	36.7	73.3	
A -16Na-2.5	—	—	200	—	600	—	—	31.4	78.6	
AS-8Na-1	—	—	—	200	600	55	—	—	55	
AS -8Na-1.5	—	—	—	200	600	44	—	—	66	
AS -8Na-2	—	—	—	200	600	36.7	—	—	73.3	
AS -8Na-2.5	—	—	—	200	600	31.4	—	—	78.6	
AS -12Na-1	—	—	—	200	600	—	55	—	55	
AS -12Na-1.5	—	—	—	200	600	—	44	—	66	
AS -12Na-2	—	—	—	200	600	—	36.7	—	73.3	0.55
AS -12Na-2.5	—	—	—	200	600	—	31.4	—	78.6	
AS -16Na-1	—	—	—	200	600	—	—	55	55	
AS -16Na-1.5	—	—	—	200	600	—	—	44	66	
AS -16Na-2	—	—	—	200	600	—	—	36.7	73.3	
AS -16Na-2.5	—	—	—	200	600	—	—	31.4	78.6	

3. Result and Discussion

3.1. Pozzolanic Activity

The hydraulic behavior of the two geopolymer binders-namely, Albite and Alum-slag—was rigorously assessed using hydrated lime ($Ca(OH)_2$) as an alkaline activator. Each dried, ground solid was combined in dry form with solid $Ca(OH)_2$ at an 80:20 mass ratio. Hydration was then initiated employing a 1:1 weight ratio of solids to water. To characterize the hydration kinetics, two key parameters were monitored at distinct curing intervals (2 and 6 hours, as well as 1, 2, and 7 days): the quantity of unreacted free lime remaining and the amount of chemically bound water. Table 4 presents the evolution of residual free lime content throughout the hydration process.

Wt. of chemical hydroxide (gm) = Molarity x volume of water (L) x specific gravity of chemical hydroxide (gm/mole)] (1)

The obtained data clearly demonstrate that the free lime content declines steadily as hydration time progresses, owing directly to its uptake through pozzolanic interaction with each of the tested solids. Alum-slag exhibits exceptionally high pozzolanic reactivity: the entire free lime reserve was exhausted within the first six hours of the hydration process. In contrast, Albite also displays appreciable pozzolanic activity, albeit more gradually, with nearly all free lime being consumed only after seven days of hydration.

Table 4. Free Lime content

Binder	CaO (%)				
	2 H	6 H	1 d	2 d	7 d
Alum-slag	0.72	0.41	0	0	0
Albite	10.92	7.72	4.56	2.11	0.36

3.2. Workability of Fresh Mortars

The flow table test, conducted in strict accordance with ASTM C230 M-08 [39] served as a definitive measure of mortar workability, reported as flow diameter percentage. OPC and LCFA mortars, yielding flow values of 56% and 63% respectively, demonstrated markedly superior workability compared to Albite- or Alum-slag-based geopolymer mortars.

This discrepancy stems directly from the elevated viscosity characteristic of the NaOH and Na_2SiO_3 alkaline solutions employed in geopolymer formulations. As clearly shown in Table 5, both increasing NaOH molarity and raising the Na_2SiO_3/NaOH ratio systematically reduce mortar flowability—each factor independently and unequivocally impairs workability. Figure 2 graphically confirms the inverse relationship between workability and both NaOH concentration and the Na_2SiO_3/NaOH ratio.

Table 5. Impact of varying Na_2SiO_3/NaOH ratios and the molarity of NaOH on Flow table %

NaOH (M)	8 M				12 M				16 M			
(Na_2SiO_3 / NaOH)	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Albite	48	46	43	43	45	43	43	39	43	40	39	35
Alum-slag	45	45	39	38	44	40	39	35	38	37	34	31

The flow table test results, expressed as flow diameter percentage according to ASTM C230 M-08 [39], revealed that both Albite-based and Alum-slag-based geopolymer mortars exhibit substantially lower workability than conventional OPC (56%) and LCFA (63%) mortars, primarily due to the high viscosity imparted by NaOH and Na_2SiO_3 alkaline activators. For Albite geopolymer mortar, workability decreased consistently with increasing NaOH molarity from 8 M to 16 M and with increasing Na_2SiO_3/NaOH ratio from 1 to 2.5. The highest workability for Albite was recorded at 8 M NaOH with a ratio of 1 (48% flow), whereas the lowest value (31% flow) occurred at 16 M with a ratio of 2.5. At 8 M, flow values dropped from 48% (ratio 1) to 43% (ratios 2 and 2.5). At 12 M, workability ranged from 45% (ratio 1) down to 38–39% for ratios 1.5 and 2, though an anomalous increase to 44% was noted at ratio 2.5. At 16 M, flow decreased progressively from 39% (ratio 1) to 35% (ratio 1.5) and further to 31% (ratio 2.5). For Alum-slag geopolymer mortar, only 8 M data were fully available: workability started at 45% for ratios 1 and 1.5, then fell to 39% at ratio 2. Compared to Albite at the same 8 M conditions, Alum-slag exhibited slightly lower maximum workability (45% vs. 48%) but a narrower reduction range (45% → 39% vs. 48% → 43%), suggesting that Alum-slag is less sensitive to the increase in Na_2SiO_3/NaOH ratio at low molarity.

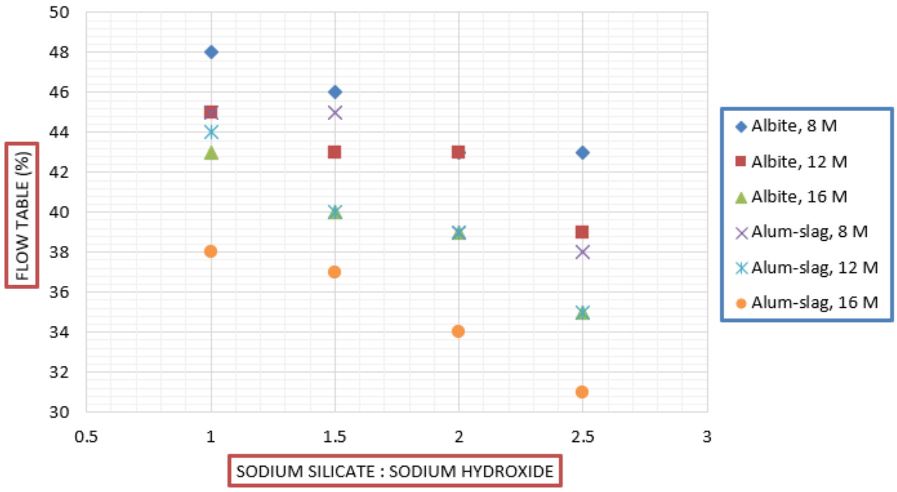

Figure 2. Effect of the NaOH molarity with different Na_2SiO_3/NaOH ratios on workability

Comparing the two geopolymer systems, Albite-based mortars show a wider workability spectrum (31–48%) that is highly responsive to both NaOH molarity and silicate-to-hydroxide ratio, making them more tunable but also more sensitive to mix design changes. In contrast, Alum-slag mortars (based on 8 M data) display more moderate and generally lower flow values, which may imply a narrower processing window. The overall reduction in workability with increasing NaOH molarity and Na_2SiO_3/NaOH ratio is attributed to the elevated viscosity of the alkaline solution, which hinders particle dispersion and mortar spreading during the flow table test. From a practical perspective, for applications requiring high fluidity (e.g., intricate casting or self-compacting geopolymer concrete), a low-molarity NaOH (8 M) combined with a low Na_2SiO_3/NaOH ratio (1) is recommended for Albite mixtures. Conversely, where lower workability is desirable (e.g., to prevent segregation or for extrusion-based additive manufacturing), a high-molarity (16 M) and high-ratio (2.5) activator can be used, provided that mechanical performance is not compromised.

3.2. Setting Time

The setting behavior of albite- and alum-slag–based geopolymer pastes was rigorously evaluated using the Vicat needle apparatus under ambient conditions in accordance with ECP 203/2007. The measured results, presented in Table 6 and Figures 3 and 4, clearly demonstrate that the initial setting time of the investigated geopolymer systems spans from 95 to 170 minutes, compared with 130 minutes for OPC and 155 minutes for LCFA. Likewise, the final setting time varies between 260 and 455 minutes, whereas OPC and LCFA exhibit values of 235 and 290 minutes, respectively.

These findings confirm that geopolymer binders provide sufficiently broad and practical setting time ranges that comply with standard requirements. A pronounced influence of NaOH molarity is evident, as increasing the concentration consistently prolongs both initial and final setting times.

This effect is more significant for the initial setting stage, showing an approximate increase of 10% (±2), compared to about 6% (±2) for the final setting time at constant Na_2SiO_3/NaOH ratios. Moreover, elevating the Na_2SiO_3/NaOH ratio further extends setting times, which can be attributed to increased solution viscosity and a higher Si/Al ratio. The dominant role of sodium ions is evident, as they actively govern the kinetics of the geo-polymerization process. In addition, the elevated silica content enhances geo-polymeric gel formation while suppressing calcium-related hydration reactions, ultimately leading to a delay in setting.

Table 6. Setting time for the different Albite and Alum-Slag geopolymer mortar mixtures

Setting time (min.)	NaOH (M)	8 M				12 M				16 M			
	(Na_2SiO_3 / NaOH)	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Albite	Initial	94	102	111	131	106	115	123	132	113	128	141	145
	Final	355	370	371	402	384	390	403	423	398	403	421	430
Alum-slag	Initial	62	71	82	103	83	91	102	103	91	100	111	122
	Final	263	270	265	275	275	290	300	310	290	305	320	330

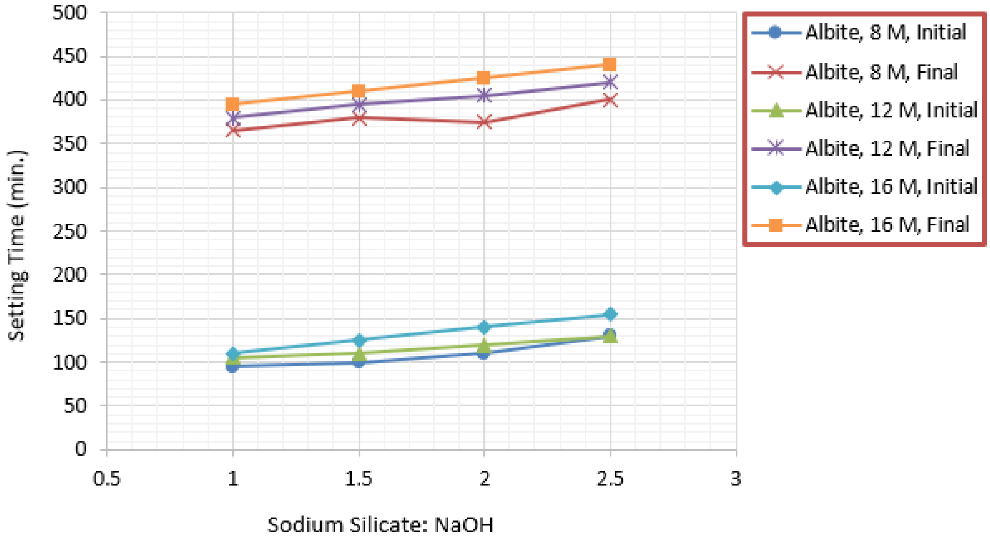

Figure 3. The impact of varying Na_2SiO_3/NaOH ratios and NaOH molarity on the albite geopolymer paste setting time.

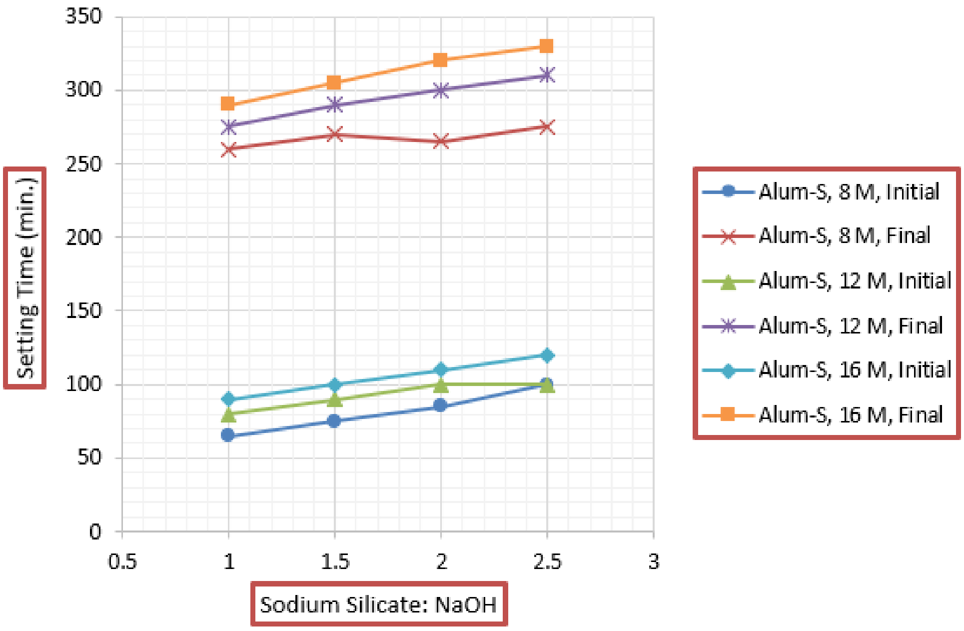

Figure 4. The impact of varying Na_2SiO_3/NaOH ratios and NaOH molarity on the alum-slag geopolymer paste setting time.

As clearly demonstrated in Figures 3 and 4, raising the molarity of the NaOH solution directly prolongs the setting time. The sodium concentration thus emerges as the dominant parameter governing setting behavior. Under low NaOH molarity conditions, the setting of geopolymers is governed primarily by the release of calcium ions—these are immediately available for reaction—whereas silicon and aluminum ions only become involved once their dissolution from the solid phases occurs.

NaOH outperformed KOH as an alkali activator, according to a comparison between calculated and, based on a prior study [20], [22], [27], [40]. In general, it can be confirmed that the alkaline metal cation functions as a structure-forming element and the OH-ions as a catalyst for reactions. More silicate and aluminate monomers are said to develop when NaOH is present. The size disparities between Na+ ions could be the cause of this. It is already reported that the Na^+ cations have better capabilities in geopolymer forming systems.

3.3. Accelerated mortar bar test

The initial length of each prismatic mortar bar (dimensions 25 × 25 × 285 mm) was recorded as the baseline reading using a digital displacement gauge. Subsequently, the specimens were immersed in a 1 M NaOH solution and remained there for a duration of 14 days prior to the next measurement, following the procedure prescribed by ASTM C1260-07 [31]. Additionally, the informative appendix of the same standard offers further interpretation criteria, which are summarized in Table 7.

Table 7. Free Lime content

ASTM C1260 [31]	
Interpretation	**14 days**
Innocuous (I)	< 0.10 %
Uncertain (U)	0.10 to 0.20 %
Potential deleterious (P-d)	≥ 0.20 %

For all 140 geopolymer mortar blends examined in this work, as well as for each cement-based and LCFA-based mortar, the expansion values were recorded after a 14-day immersion period. These measured expansions are compiled in Table 8. The data clearly reveal that raising both the NaOH molarity and the Na_2SiO_3/NaOH ratio leads to a steady but modest increase in expansion.

Table 8. ASTM C1260 Mortar bar Expansion in 1M NaOH (80°C), after 14 days [%]

Expansion	NaOH (M)	8 M				12 M				16 M			
	(Na_2SiO_3 / NaOH)	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Albite	Expansion %	0.01	0.00	0.01	0.02	0.01	0.03	0.05	0.05	0.09	0.12	0.11	0.12
	ASTM Classification	I	I	I	I	I	I	I	I	I	U	U	U
Alum-slag	Expansion %	0.05	0.06	0.07	0.09	0.08	0.09	0.11	0.11	0.08	0.09	0.11	0.13
	ASTM Classification	I	I	I	I	I	I	U	U	I	I	U	U

The accelerated mortar bar test (AMBT) results presented in Table 9 reveal distinct expansion behaviors for Albite-based and Alum-slag-based geopolymer mortars when exposed to 1M NaOH at 80°C for 14 days, as per ASTM C1260-07. For Albite-based mixtures, the expansion values increase progressively with higher NaOH molarity and higher Na_2SiO_3/NaOH ratios. At 8M NaOH, all expansions are below 0.02%, comfortably falling within the "Innocuous (I)" classification (<0.10%). At 12M NaOH, expansions remain mostly innocuous (0.01–0.05%), except at the highest ratio of 2.5, where 0.05% still qualifies as I. However, at 16M NaOH, a clear threshold is crossed: expansions range from 0.09% to 0.12%, with the 0.09% value remaining innocuous, while values of 0.11% and 0.12% enter the "Uncertain (U)" category (0.10–0.20%). In contrast, Alum-slag-based mortars exhibit slightly higher baseline expansions. At 8M NaOH, expansions range from 0.05% to 0.09%, all innocuous. At 12M NaOH, expansions reach 0.11% at ratios of 2 and 2.5, again falling into the uncertain zone. Interestingly, at 16M NaOH, expansions vary between 0.08% and 0.13%, with the lower values (0.08–0.09%) remaining innocuous, while higher ratios again produce uncertain expansions (0.11–0.13%). Notably, no mixture from either geopolymer type reached the "Potential Deleterious (P-d)" threshold of ≥0.20%, indicating that all formulations remain within acceptable limits for alkali-silica reaction (ASR) susceptibility under these test conditions.

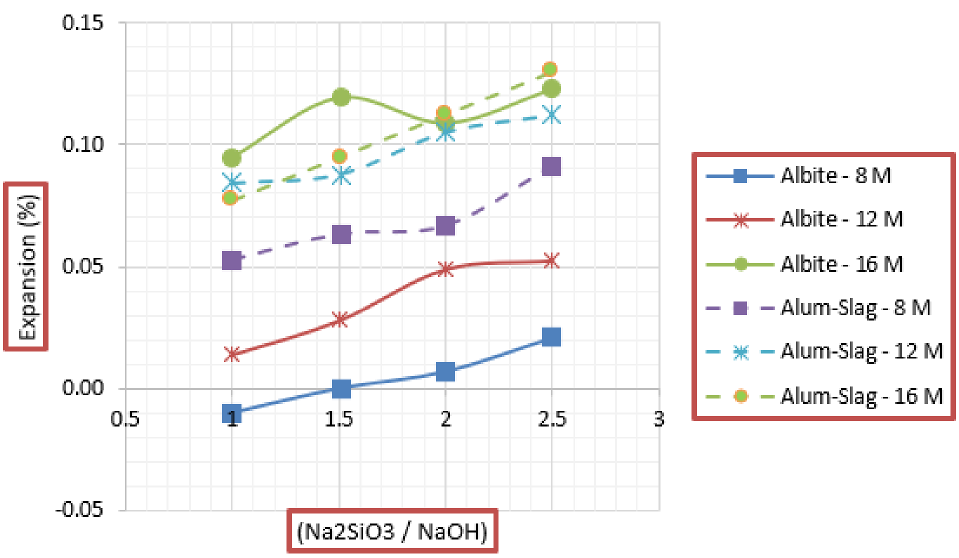

Figure 5. Effect of the NaOH molarity with different Na_2SiO_3/NaOH ratios on Expansion (%) of Albite and Alum-Slag geopolymer mortar.

From the perspective of the alkaline solution's influence, the results demonstrate that both the molarity of NaOH and the Na_2SiO_3/NaOH ratio play critical, interactive roles in controlling expansion. For Albite-based geopolymers, the transition from innocuous to uncertain behavior occurs predominantly at 16M NaOH combined with higher silicate ratios (≥1.5), suggesting that highly concentrated and highly alkaline activators increase the risk of ASR-like expansion. This may be attributed to enhanced dissolution of reactive silica from albite under severe alkaline conditions. For Alum-slag-based mortars, the expansion pattern is less monotonic: at 16M NaOH, the expansions at ratios 1 and 1.5 (0.08% and 0.09%) are actually lower than those at 12M with ratio 2.5 (0.11%), indicating a possible optimum in activator composition that minimizes expansion. This non-linear behavior could be due to the formation of a more stable geopolymer gel or better packing at higher molarities when the silicate ratio is not excessive. Overall, both geopolymer types are predominantly innocuous under AMBT, but the Albite-based system shows a clearer sensitivity to increased alkalinity, while the Alum-slag system exhibits moderate expansions that occasionally enter the uncertain range. For practical applications, maintaining NaOH molarity at 12M or below, and limiting the Na_2SiO_3/NaOH ratio to 2.0 or less, appears advisable to ensure innocuous behavior for both binder types. These findings underscore the importance of tailoring the alkaline activator composition not only for mechanical performance but also for long-term durability against alkali-induced expansion.

Furthermore, ordinary Portland cement and low-calcium fly ash mortars exhibit substantially lower expansion (0.002% and 0.016%, respectively) than either Albite- or Alum-slag-based geopolymer mortars. This discrepancy likely arises because the NaOH and Na_2SiO_3 alkaline activators employed in the geopolymer mixtures can undergo chemical interaction with the 1 M NaOH solution used during the accelerated heat treatment. As illustrated in Figure 5, for Albite-based mixtures activated with NaOH, the impact on accelerated mortar bar test (AMBT) expansion is pronounced: the relative increases reach approximately 47.6%, 28%, and 73.17% for the 8 M, 12 M, and 16 M mortar series, respectively. Likewise, raising the Na_2SiO_3/NaOH ratio further amplifies the expansion. In the case of Alum-slag mixtures activated with NaOH, the effect on AMBT is even more striking: expansion increments of roughly 58%, 75%, and 59% are observed for the 8 M, 12 M, and 16 M mortar bars, respectively, and again, increasing the Na_2SiO_3/NaOH ratio consistently elevates the expansion values.

4. Conclusions

Based on the experimental results, the following conclusions could be drawn:

1. Compared to geopolymer binder mortars, OPC and LCFA mortars demonstrate higher workability, which is attributed to the higher viscosity of the liquids employed in geopolymer production.
2. In geopolymer mortars containing either albite or alum-slag, increasing the NaOH molarity and the Na_2SiO_3 content reduces workability.
3. The molarity of the NaOH solution exerts a more pronounced influence on the initial setting time than on the final setting time.
4. Raising the Na_2SiO_3/NaOH ratio prolongs both the initial and final setting times. This behavior is likely due to the increased viscosity of the alkaline solution and the higher Si/Al ratio. The sodium content appears to be the primary factor controlling setting time, possibly because Na^+ cations act as a reaction catalyst.

5. A higher silicon content promotes geo-polymerization reactions while hindering calcium hydration reactions (noting that calcium is present only in small amounts in albite, alum-slag, and LCFA), thereby increasing the setting time.
6. High specific gravity, high viscosity coefficient, and low water content of the soluble silicate solution are critical criteria for excluding unsuitable activators. Consequently, NaOH is preferable to other alkaline activators.
7. In the accelerated mortar bar test (AMBT), NaOH and KOH solutions at concentrations of 8 M and 12 M were classified as innocuous according to ASTM C1260-07.
8. The results indicate that by varying the proportions and concentration of the alkaline solution, geopolymer mixtures can achieve a wide range of properties, including workability, setting time, and compressive strength.
9. The concentration of NaOH as well as the Na_2SiO_3/NaOH ratio, affect workability and setting time in a similar manner: increasing these parameters leads to reduced workability and extended setting times.
10. Based on the observed effects on workability, initial and final setting times, and AMBT performance, NaOH is considered a more effective alkaline activator.
11. The results demonstrate that both albite and alum-slag can be classified as acceptable raw materials for geopolymer production.

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References

[1] B. Walkley, X. Ke, O. H. Hussein, S. A. Bernal, and J. L. Provis, "Incorporation of strontium and calcium in geopolymer gels," *J. Hazard. Mater.*, vol. 382, p. 121015, 2020, doi: https://doi.org/10.1016/j.jhazmat.2019.121015.

[2] X. Huang, Y. Tian, J. Jiang, X. Lu, Z. He, and K. Jia, "Mechanical properties and enhancement mechanism of iron ore tailings as aggregate for manufacturing ultra-high performance geopolymer concrete," *Constr. Build. Mater.*, vol. 439, p. 137362, 2024, doi: https://doi.org/10.1016/j.conbuildmat.2024.137362.

[3] S. Jain, N. Banthia, and T. Troczynski, "Leaching of immobilized cesium from NaOH-activated fly ash-based geopolymers," *Cem. Concr. Compos.*, vol. 133, p. 104679, 2022, doi: https://doi.org/10.1016/j.cemconcomp.2022.104679.

[4] X. Zhang *et al.*, "Porous geopolymer composites: A review," *Compos. Part A Appl. Sci. Manuf.*, vol. 150, p. 106629, 2021, doi: https://doi.org/10.1016/j.compositesa.2021.106629.

[5] S. K. John, Y. Nadir, and K. Girija, "Effect of source materials, additives on the mechanical properties and durability of fly ash and fly ash-slag geopolymer mortar: A review," *Constr. Build. Mater.*, vol. 280, p. 122443, 2021, doi: 10.1016/j.conbuildmat.2021.122443.

[6] K. Chen, D. Wu, M. Yi, Q. Cai, and Z. Zhang, "Mechanical and durability properties of metakaolin blended with slag geopolymer mortars used for pavement repair," *Constr. Build. Mater.*, vol. 281, p. 122566, 2021, doi: 10.1016/j.conbuildmat.2021.122566.

[7] J. Matsimbe, M. Dinka, D. Olukanni, and I. Musonda, "Performance evaluation and mix design of ambient-cured fly ash-phosphogypsum blended geopolymer paste and mortar," *Results Eng.*, vol. 24, p. 103280, 2024, doi: https://doi.org/10.1016/j.rineng.2024.103280.

[8] A. El Abd *et al.*, "Neutron imaging of moisture transport, water absorption characteristics and strength properties for fly ash/slag blended geopolymer mortars: Effect of drying temperature," *Constr. Build. Mater.*, vol. 449, p. 138436, 2024, doi: https://doi.org/10.1016/j.conbuildmat.2024.138436.

[9] M. Shaaban, W. F. Edris, E. Odah, M. S. Ezz, and A. A. A. Al-sayed, "A Green Way of Producing High Strength Concrete Utilizing Recycled Concrete," vol. 9, no. 10, 2023.

[10] A. A. K. A. Al Sayed, Q. F. Al-Waked, S. M. M. Shawky, H. M. Al-jabali, and W. Fouad Edris, "Effect of alkali activated limestone-silica fume blended precursor on performance enhancement of recycled aggregate concrete," *Case Stud. Constr. Mater.*, vol. 19, no. September, p. e02661, 2023, doi: 10.1016/j.cscm.2023.e02661.

[11] J. Davidovits, "Properties of Geopolymer Cements," *First Int. Conf. Alkaline Cem. Concr.*, pp. 131–149, 1994.

[12] J. Hwalla, H. El-Hassan, A. El-Mir, J. J. Assaad, and T. El-Maaddawy, "Development of geopolymer and cement-based shotcrete mortar: Impact of mix design parameters and spraying process," *Constr. Build. Mater.*, vol. 449, p. 138457, 2024, doi: https://doi.org/10.1016/j.conbuildmat.2024.138457.

[13] A. M. Rashad, G. M. F. Essa, W. M. Morsi, and E. A. Fahmy, "Calcium nitrate as a modifier agent for metakaolin-based geopolymer mortar," *Constr. Build. Mater.*, vol. 456, p. 139199, 2024, doi: https://doi.org/10.1016/j.conbuildmat.2024.139199.

[14] H. A. A. E. Ghanim, U. J. Alenagram, N. M. Bunnori, and M. S. I. Ibrahim, "Innovative In-House Sodium Silicate Derived from Coal Bottom Ash and Its Impact on Geopolymer Mortar," *J. Build. Eng.*, p. 111428, 2024, doi: https://doi.org/10.1016/j.jobe.2024.111428.

[15] Y. Chen, C. Zou, J. S. Yeo, J. Lin, T. H. Tan, and K. H. Mo, "Valorization of high-volume crushed waste glass as fine aggregate in foamed geopolymer," *Case Stud. Constr. Mater.*, vol. 22, p. e04202, 2025, doi: https://doi.org/10.1016/j.cscm.2025.e04202.

[16] T. Bezabih, D. Sinkhonde, and D. Mirindi, "Revisiting the surface characteristics of fly ash-teff straw ash-based geopolymer mortars in the context of fractal theory," *Results in Surfaces and Interfaces*, vol. 17, p. 100292, 2024, doi: https://doi.org/10.1016/j.rsurfi.2024.100292.

[17] C. K. Madheswaran, P. S. Ambily, J. K. Dattatreya, and G. Ramesh, "Experimental Studies on Behaviour of Reinforced Geopolymer Concrete Beams Subjected to Monotonic Static Loading," *J. Inst. Eng. Ser. A*, vol. 96, no. 2, pp. 139–149, 2015, doi: 10.1007/s40030-

015-0115-1.

[18] S. Lekshmi, J. Sudhakumar, and S. Thomas, “Application of clay in geopolymer system: A state-of-the-art review,” *Mater. Today Proc.*, 2023, doi: https://doi.org/10.1016/j.matpr.2023.04.083.

[19] S. S. Chanda and S. Guchhait, “A comprehensive review on the factors influencing engineering characteristics of lightweight geopolymer concrete,” *J. Build. Eng.*, vol. 86, p. 108887, 2024, doi: https://doi.org/10.1016/j.jobe.2024.108887.

[20] S. Chowdhury, S. Mohapatra, A. Gaur, G. Dwivedi, and A. Soni, “Study of various properties of geopolymer concrete - A review,” *Mater. Today Proc.*, vol. 46, no. xxxx, pp. 5687–5695, 2020, doi: 10.1016/j.matpr.2020.09.835.

[21] T. Udhaya Kumar and M. Vinod Kumar, “Investigation on mechanical properties of geopolymer aggregate concrete,” *Mater. Today Proc.*, vol. 43, no. xxxx, pp. 1220–1225, 2020, doi: 10.1016/j.matpr.2020.08.758.

[22] T. Bezabih, D. Sinkhonde, and D. Mirindi, “On the surface roughness properties of fly ash-based geopolymer mortars with teff straw ash from the image analysis viewpoint,” *Green Technol. Sustain.*, vol. 3, no. 1, p. 100127, 2025, doi: https://doi.org/10.1016/j.grets.2024.100127.

[23] S. Madhusudhana, J. N. Prakash, and L. H. Manjunath, “Study on preparation and mechanical characterization of alluminium-albite composites using powder metallurgy technique,” *Mater. Today Proc.*, vol. 54, pp. 390–394, 2022, doi: https://doi.org/10.1016/j.matpr.2021.09.456.

[24] G. A. Khater, A. A. El-Kheshen, M. M. Farag, H. Shendy, and N. H. S. Nasralla, “Preparation and characterization of low-cost albite and wollastonite glass-ceramics based on natural raw materials,” *Next Mater.*, vol. 9, p. 101183, 2025, doi: https://doi.org/10.1016/j.nxmate.2025.101183.

[25] X. Zheng, C. Zhang, H. Ma, H. Yang, Y. Zhao, and B. Liu, “Effect of albite on shrinkage and carbonation resistance of alkali-activated slag,” *Constr. Build. Mater.*, vol. 409, p. 134141, 2023, doi: https://doi.org/10.1016/j.conbuildmat.2023.134141.

[26] S. Lawanwadeekul, P. Chindaprasirt, N. Ariyajinno, A. Srisuwan, and N. Phonphuak, “Acid-resistant clay bricks incorporating bottom ash and waste glass strengthened by mullite suppression and albite formation,” *Next Mater.*, vol. 11, p. 101610, 2026, doi: https://doi.org/10.1016/j.nxmate.2026.101610.

[27] N. B. Singh and B. Middendorf, “Geopolymers as an alternative to Portland cement: An overview,” *Constr. Build. Mater.*, vol. 237, pp. 1–15, 2020, doi: 10.1016/j.conbuildmat.2019.117455.

[28] S. Chowdhury, S. Mohapatra, A. Gaur, G. Dwivedi, and A. Soni, “Study of various properties of geopolymer concrete - A review,” *Mater. Today Proc.*, vol. 46, no. July 2024, pp. 5687–5695, 2020, doi: 10.1016/j.matpr.2020.09.835.

[29] W. Huang and H. Wang, “Formulation development of metakaolin geopolymer with good workability for strength improvement and shrinkage reduction,” *J. Clean. Prod.*, vol. 434, p. 140431, 2024, doi: https://doi.org/10.1016/j.jclepro.2023.140431.

[30] S. S. Rahman and M. J. Khattak, “Feasibility of Reclaimed Asphalt Pavement Geopolymer Concrete as a Pavement Construction Material,” *Int. J. Pavement Res. Technol.*, vol. 16, no. 4, pp. 888–907, 2023, doi: 10.1007/s42947-022-00169-8.

[31] M. Cabinets, M. Rooms, B. Statements, and T. Method, “ASTM C1260 Standard test method for potential alkali reactivity of aggregates (mortar_bar method), ASTM International, West Conshohocken, PA,” pp. 12–16, 2014.

[32] B. Poletanovic, K. Kopecsko, and I. Merta, “Fibre hornification improves the long-term properties of hemp fibre-reinforced fly ash-based geopolymer mortar,” *Constr. Build. Mater.*, vol. 446, p. 137957, 2024, doi: https://doi.org/10.1016/j.conbuildmat.2024.137957.

[33] P. W. Ariyadasa, A. C. Manalo, W. Lokuge, V. Aravinthan, K. Pasupathy, and A. Gerdes, “Bond performance of fly ash-based geopolymer mortar in simulated concrete sewer substrate,” *Constr. Build. Mater.*, vol. 446, p. 137927, 2024, doi: https://doi.org/10.1016/j.conbuildmat.2024.137927.

[34] M. S. Khan, M. Ismail, X. Chen, and R. Ahmad, “Novel upcycling of aluminum electrolysis waste into high value albite (NaAlSi3O8) ceramic material for UV reflective coatings,” *J. Alloys Compd.*, vol. 1062, p. 187568, 2026, doi: https://doi.org/10.1016/j.jallcom.2026.187568.

[35] Y. Sun, S. Liu, Q. Wen, J. Guo, and Z. Yang, “Experimental and DFT simulation studies on the mechanism of acid and alkali promoted

dissolution of albite," *Appl. Surf. Sci.*, vol. 641, p. 158475, 2023, doi: https://doi.org/10.1016/j.apsusc.2023.158475.

[36] A. Rezzoug, N. Leklou, K. Ayed, and H. Maryam, "Enhancing geopolymer mortars for environmental sustainability: A novel approach using frits and ceramic waste," *Next Res.*, vol. 1, no. 2, p. 100024, 2024, doi: https://doi.org/10.1016/j.nexres.2024.100024.

[37] A. Rezzoug, K. Ayed, and N. Leklou, "Thermal, mechanical and microstructural properties of geopolymer mortars derived from ceramic sanitary-ware wastes: Pathway to net zero emission," *Ceram. Int.*, 2024, doi: https://doi.org/10.1016/j.ceramint.2024.10.414.

[38] C. Ag-, B. Statements, and W. Pycnometer, "Standard Test Method for iTeh Standards iTeh Standards," pp. 22–25, 2015, doi: 10.1520/C1038.

[39] ASTM, "ASTM C230 Standard Specification for Flow Table for Use in Tests of Hydraulic Cement," *Annu. B. ASTM Stand.*, pp. 4–9, 2010.

[40] A. Hassani and F. Kazemian, "Investigating geopolymer mortar incorporating industrial waste using response surface methodology: A sustainable approach for construction materials," *Case Stud. Constr. Mater.*, vol. 21, p. e03609, 2024, doi: https://doi.org/10.1016/j.cscm.2024.e03609.