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EXPERIMENTAL STUDY ON HIGH-CALCIUM ALKALI-ACTIVATED MATERIALS: SLAG, PALM KERNEL SHELL ASH, AND CLASS C FLY ASH-BASED MORTAR

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Abstract

This study investigates the development of sustainable high-calcium alkali-activated mortar incorporating Ground Granulated Blast Furnace Slag (GGBS), Palm Kernel Shell Ash (PKSA), and Class C Fly Ash (CFA) as hybrid binders, using locally available Bholari brown sand as the sole fine aggregate. Mortar mixes were activated using sodium hydroxide (NaOH) solutions with molarities ranging from 8 M to 16 M, while the sand-to-binder (S/B) ratio was maintained at 2.0 to evaluate its influence on fresh and mechanical properties. Cylindrical specimens (100 mm diameter × 200 mm height) were initially cured at room temperature or in an oven at 60 °C for 5 hours and then stored under ambient laboratory conditions until testing. Experimental results indicate that compressive strength increased significantly with NaOH molarity up to an optimum range (12–14 M), after which slight reductions occurred at higher molarity levels due to rapid gel precipitation and microstructural defects. Oven curing enhanced early-age strength and densified the matrix. The 28-day compressive strength of 50% Slag + 50% CFA mixes reached up to 55 MPa, while PKSA-rich mixes achieved approximately 35–40 MPa. The study concludes that hybrid high-calcium binders, combined with locally available Bholari sand, can produce high-performance, eco-friendly mortar suitable for sustainable construction.

1. INTRODUCTION

Concrete production is a major source of global CO_2 emissions, primarily from ordinary Portland cement (OPC) production (~7–8% of total emissions)[1].Different types of alumino simicate materiasl contain high calcium called alakli activated and low calcium materials called Geopolymer (waste glass powder, fly ash , sewage sludge ash, metakoilin)[2]. Alkali-activated materials (AAMs) using industrial and agricultural by-products provide a low-carbon alternative while improving durability but high calcium materials main challenges is deterioration of cocnrete structures under low pH environemnts because of leaching behaviour[3]–[6] High-calcium materials, such as GGBS, PKSA, and CFA, serve as reactive binders for AAMs[7]–[12]. Slag provides rapid C–A–S–H gel formation. High-calcium fly ash (HCFA) contributes silica and moderate calcium for N–A–S–H gel formation, and PKSA is a silica-rich, low-calcium by-product offering long-term strength contribution[13]. HCFA a residue of high-temperature coal combustion at thermal power plants, in combination with sodium carbonate, presents an effective hardening activator of ground granulated blast-furnace slag (GGBFS)[14]–[17]. Substitution of 10%–30% of GGBFS by HCFA and premixing of 1%–3% Na_2CO_3 into this dry binary binder has been shown to give mortar compressive strength of 10–30 MPa at 7 days and 30–45 MPa at 28 days when moist-cured at ambient temperature[18]. High-calcium fly ash produced from low-temperature combustion of fuel, like in circulating fluidized bed technology, reacts with water readily and is itself a good hardening activator for GGBFS, so introduction of Na_2CO_3 into such a mix has no noticeable effect on mortar strength. However, low-temperature HCFA has higher water demand, and the strength of mortar is compromised by this factor. As of today, research is still ongoing, and further data on durability of the proposed GGBFS-HCFA binder is expected[19]–[22].

Studies on hydration of binders based on GGBFS indicate that alkali silicates and hydroxides are preferred as hardening activators since they achieve the highest strength characteristics, but these activators have disadvantages that limit practical implementation. These include industrial safety issues due to high alkalinity and significant shrinkage of GGBFS geopolymers[2]–[4], [6], [7], [10], [11]. Additionally, these activators are typically used as concentrated aqueous solutions, since solid sodium and potassium silicates are expensive. Consequently, the solid binder and liquid activator must be stored separately and mixed in-situ before application[5], [21], [25], [26]. For wide commercial use, it is important that the processing resembles traditional concrete or mortar practices, with the binder delivered as a “one-pack” dry mix that includes all necessary activators[27]–[29].

Compared to alkali silicates, sodium and potassium carbonates do not provide high early strength but are safer to handle, cheaper, available in bulk solid form, and cause 3–6 times lower shrinkage during hardening. The challenge is that the initial pH (~11) is insufficient to promote rapid slag dissolution. Combining carbonates with calcium-releasing compounds such as $Ca(OH)_2$ or high-calcium fly ash increases pH and accelerates C–A–S–H formation, enhancing early strength. High-calcium fly ash contains free CaO, $CaSO_4$, and $3CaO{\cdot}Al_2O_3$, capable of hydration to produce C–S–H, gypsum, and ettringite. In combination with Na_2CO_3, the pH of the suspension rises above 13, stimulating both slag and fly ash hydration[30], [31].

High-calcium alkali-activated mortars (HCAAMs) produced using calcium-rich precursors such as slag and Class C fly ash show rapid reactions and early strength development even under ambient curing. However, these reactions can reduce workability due to accelerated setting. HCAAMs are part of the broader family of AAMs, in which aluminosilicate-rich powders react with alkaline activators to form binder phases. High-calcium systems, including GGBFS and high-calcium fly ash, are often combined with silica sand to make mortar[32]. Calcium accelerates hardening and can reduce or eliminate the need for heat curing, making high-calcium fly ash suitable as a base material for geopolymer or alkali-activated binders[33]. The behavior of high-calcium systems varies depending on precursor type, blend design, and activator chemistry. Limited performance data

exists for mortars made with binary and ternary blends under ambient curing[34]. High calcium improves early reactions but may cause flash setting, particularly in ASTM Class C fly ash mortars [33]. Overall, literature frames HCAAMs as promising for practical mortar production because they can achieve useful compressive strength at ambient temperature, including slag-rich and high-calcium fly ash systems[35]. Fresh-state properties such as workability, flow, and setting behavior are influenced by calcium content and activator intensity. Higher calcium or stronger activators accelerate setting, reducing workability[11], [36]. Slag-rich systems provide high compressive strength but may require careful adjustment of water content and admixtures to maintain flow[37], [38]. Blending precursors and using chemical admixtures can tune workability without compromising strength[34], [39], [40]. Compressive strength varies widely in high-calcium systems. Slag-rich mortars can achieve 35–90 MPa at 28 days depending on mix design, curing, and activator[41], [42]. Hybrid blends (e.g., GGBFS/fly ash) benefit from calcium-silica synergy, achieving high early and later-age strength[43].Strength development may continue under aggressive exposure or cyclic conditions without significant loss whereas low-calcium systems may plateau or lose strength if early gel precipitation is unbalanced[44]. Key factors controlling fresh and hardened performance include precursor chemistry, activator dosage and ratios, water-to-solid ratio, and blending of calcium-bearing and siliceous powders. Optimal performance requires balancing calcium content with reactive aluminosilicates and proper alkali activation .Bholari brown sand, a local fine aggregate in Pakistan, reduces environmental impact and influences mechanical performance, particularly with respect to NaOH molarity and sand-to-binder ratio. This study investigates six binder combinations 100% Slag, 100% PKSA, 100% CFA, 50% Slag + 50% PKSA, 50% Slag + 50% CFA, and 50% PKSA + 50% CFA—under NaOH molarities of 8–16 M and curing conditions (room temperature versus oven at 60 °C) to evaluate compressive and tensile strength development using locally available materials.

2. Materials and Methodology

2.1 Materials

In this study, the main materials used included Bholari brown sand as fine aggregate,binder such as Ground Granulated Blast Furnace Slag (GGBS), Palm Kernel Shell Ash (PKSA), Class C Fly Ash (CFA), and activators sodium hydroxide (NaOH) solution, and sodium silicate (Na_2SiO_3) solution. **Table 1** presents the XRF of the binders, illustrating their chemical composition. Each constituent plays a specific role: slag, PKSA, and CFA provide aluminosilicate phases for geopolymerization, slag and CFA contribute calcium for hybrid C–A–S–H/N–A–S–H gel formation, Bholari sand acts as the fine aggregate, and the alkaline activator initiates dissolution and gel development.

Ground Granulated Blast Furnace Slag (GGBS) is a by-product of steel manufacturing, abundant in Pakistan. It was ground into a fine powder (median particle size ~15 µm) to enhance reactivity. The high calcium content promotes rapid formation of C–A–S–H gel, contributing to early-age strength.

Palm Kernel Shell Ash (PKSA) is an agricultural waste produced from burning palm kernel shells under controlled conditions and grinding into fine powder. Its silica-rich composition supports geopolymerization and improves long-term strength.

Class C Fly Ash (CFA) is a low-cost industrial by-product rich in silica and moderate calcium. CFA contributes to the formation of N–A–S–H gel, improving strength and durability over time.

Bholari Brown Sand, sourced locally from the Jamshoro Bholari region, was used as the fine aggregate. It exhibited a specific gravity of 2.56, particle density 2.56 g/cm³, and fineness modulus of 2.63. Prior to mixing, sand was oven-dried to remove moisture and ensure uniformity.

The alkaline activator consisted of a combination of NaOH solution and commercial liquid sodium silicate. Sodium silicate contained approximately 25–30 wt% SiO_2 and 10–13 wt% Na_2O, with a SiO_2/Na_2O modulus of 2.0–3.0 and density 1.4–1.6 g/cm³. Sodium hydroxide solutions of 8M, 10M, 12M, 14M, and 16 M were prepared by dissolving analytical-grade NaOH pellets in

distilled water and cooling for 24 hours prior to use to ensure stability[45].

Table 1. XRF of Slag, PKSA, and CFA (by wt %).

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
Slag	36	14	2.5	42	6	1	0.5	1
PKSA	45	12	3.7	28	5	1.1	0.4	4.2
CFA	48	10	7	25	1.5	1	1	2.5

2.2 Mix Proportions

All mortar mixtures were proportioned on a 1 m^3 basis with a constant binder content of 500 kg/m^3. The activator-to-binder ratio (AA/B) was maintained at 0.60, and the sodium silicate to sodium hydroxide (SS/SH) ratio was 2.5. Sand-to-binder ratio was fixed at 2.0 for all mixes. Six binder combinations were investigated: 100% Slag, 100% PKSA, 100% CFA, 50% Slag + 50% PKSA, 50% Slag + 50% CFA, 50% PKSA + 50% CFA. NaOH molarity levels ranged from 8 to 16 M. The high-calcium alkali-activated mortar mixes were designed with six binder combinations, using 500 kg/m^3 total binder content and a sand-to-binder ratio of 2.0. The binder compositions included 100% Slag (M-S100), 100% PKSA (M-PK100), 100% CFA (M-CFA100), and hybrid combinations of 50% Slag + 50% PKSA (M-S50PK50), 50% Slag + 50% CFA (M-S50CFA50), and 50% PKSA + 50% CFA (M-PK50CFA50). Sodium hydroxide molarity was varied from 8 M to 16 M, while the sodium silicate to NaOH ratio was maintained at 2.5 and the activator-to-binder ratio at 0.6. For each mix, the corresponding fine aggregate content was adjusted to maintain the S/B ratio, with 1000 kg/m^3 used for all mixes at S/B = 2. The resulting matrix design allowed systematic evaluation of the effects of binder type, hybridization, and NaOH molarity on compressive and tensile strength development across early and 28-day curing periods.

Table 2. Mix Design of High-Calcium Mortar Using Bholari Sand.

Mix ID	Binder Composition	NaOH (M)	SS/SH	AA/B	Sand/Binder
M1	100% Slag	8–16	2.5	0.6	2
M2	100% PKSA	8–16	2.5	0.6	2
M3	100% CFA	8–16	2.5	0.6	2
M4	50% Slag + 50% PKSA	8–16	2.5	0.6	2
M5	50% Slag + 50% CFA	8–16	2.5	0.6	2
M6	50% PKSA + 50% CFA	8–16	2.5	0.6	2

2.3 Mixing, Casting, and Curing

Dry materials, including Slag, PKSA, CFA, and sand, were first homogenized in a laboratory mixer for approximately 2 minutes. The pre-prepared alkaline activator solution was then added gradually, and mixing continued for an additional 3–4 minutes until a uniform mortar was obtained. Fresh properties, including flowability and setting behavior, were evaluated immediately after mixing. Alkali activated material based mortar was cast into 100 mm × 200 mm cylindrical molds for compressive and tensile strength measurements. After casting, specimens were sealed to minimize moisture loss and subjected to oven curing at 60 °C for 5 hours. Following curing, the specimens were demolded and stored under ambient laboratory conditions until testing at 7 and 28 days.

3. Results and Discussion

3.1 Compressive Strength

Figure 1, Figure 2 and **Figure 3** presents the experimenral outcomes 7-day and 28-day compressive strengths for all six mortar mixes activated with 8M-16 M NaOH, SS/SH = 2.5,

AA/B = 0.6, and sand-to-binder ratio of 2. Oven curing at 60 °C for 5 hours.

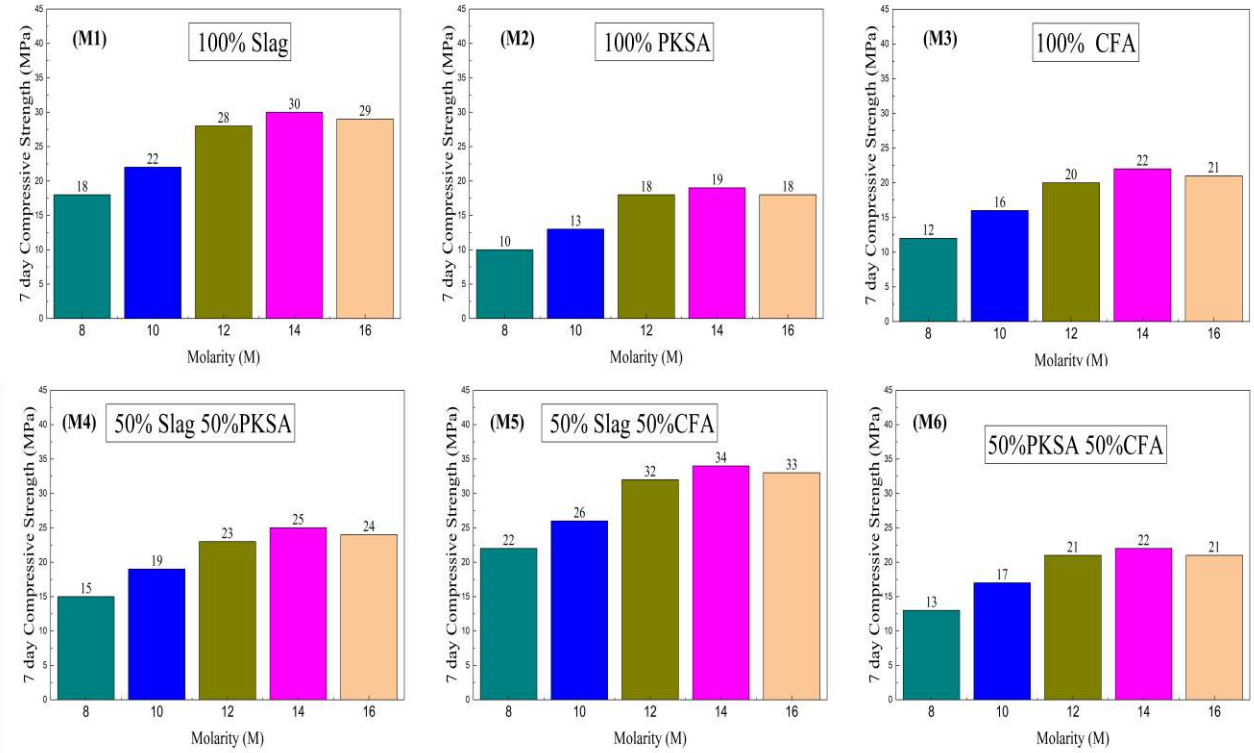

Figure 1. 7 days compressive strenght of all mix (M1-M6)

The experimental results 7-day and 28-day compressive strengths of all six high-calcium alkali-activated mortar mixes are shown in Table 1. Slag-rich mixes, particularly M1 (100% Slag), achieved high early strength (28 MPa at 7 days) and 28-day strength (38 MPa), attributable to the rapid formation of C–A–S–H gel, which fills capillary pores, reduces porosity, and densifies the matrix, consistent with observations by Palomo et al. (2014) and Fernández-Jiménez et al. (2018). The low-porosity microstructure observed in slag-rich systems allows efficient load transfer, which explains the high compressive strength. Oven curing (60 °C for 5 h) further accelerates geopolymerization, producing 10–20% higher early-age strength compared to ambient curing (Gomaa et al., 2017), while 28-day strengths converge due to slow ongoing reaction of residual aluminosilicates.

The 100% PKSA mix (M2) exhibited lower compressive strength (7-day 18 MPa, 28-day 25 MPa) due to its low calcium content, which limits the rapid formation of C–A–S–H gel. Instead, gel formation relies primarily on slower N–A–S–H network development, as reported in similar agricultural waste-based geopolymer studies [7]–[12].The low early strength highlights the importance of NaOH molarity: higher concentrations promote the dissolution of silica and alumina, enhancing the rate of geopolymerization.

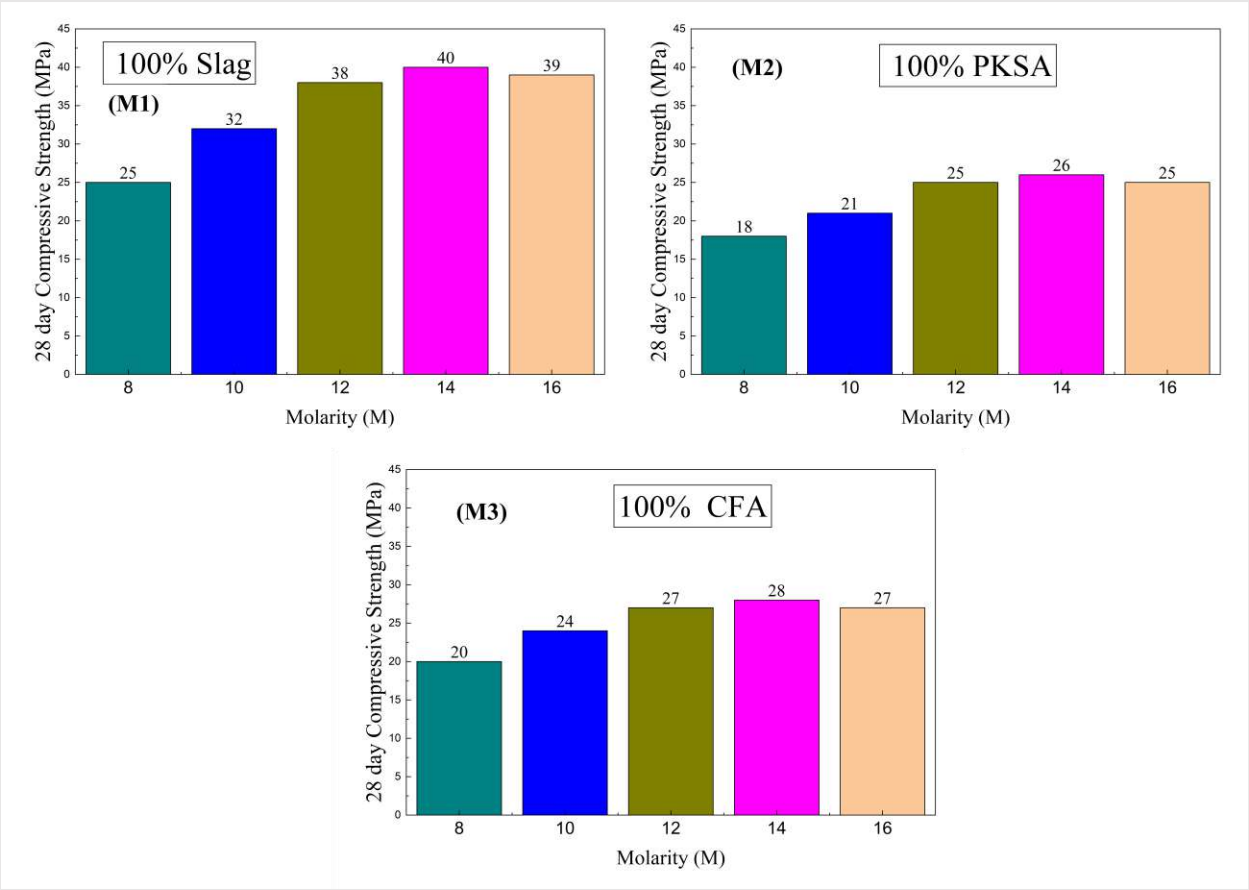

Figure 2. 28 days compressive strength of single binders.

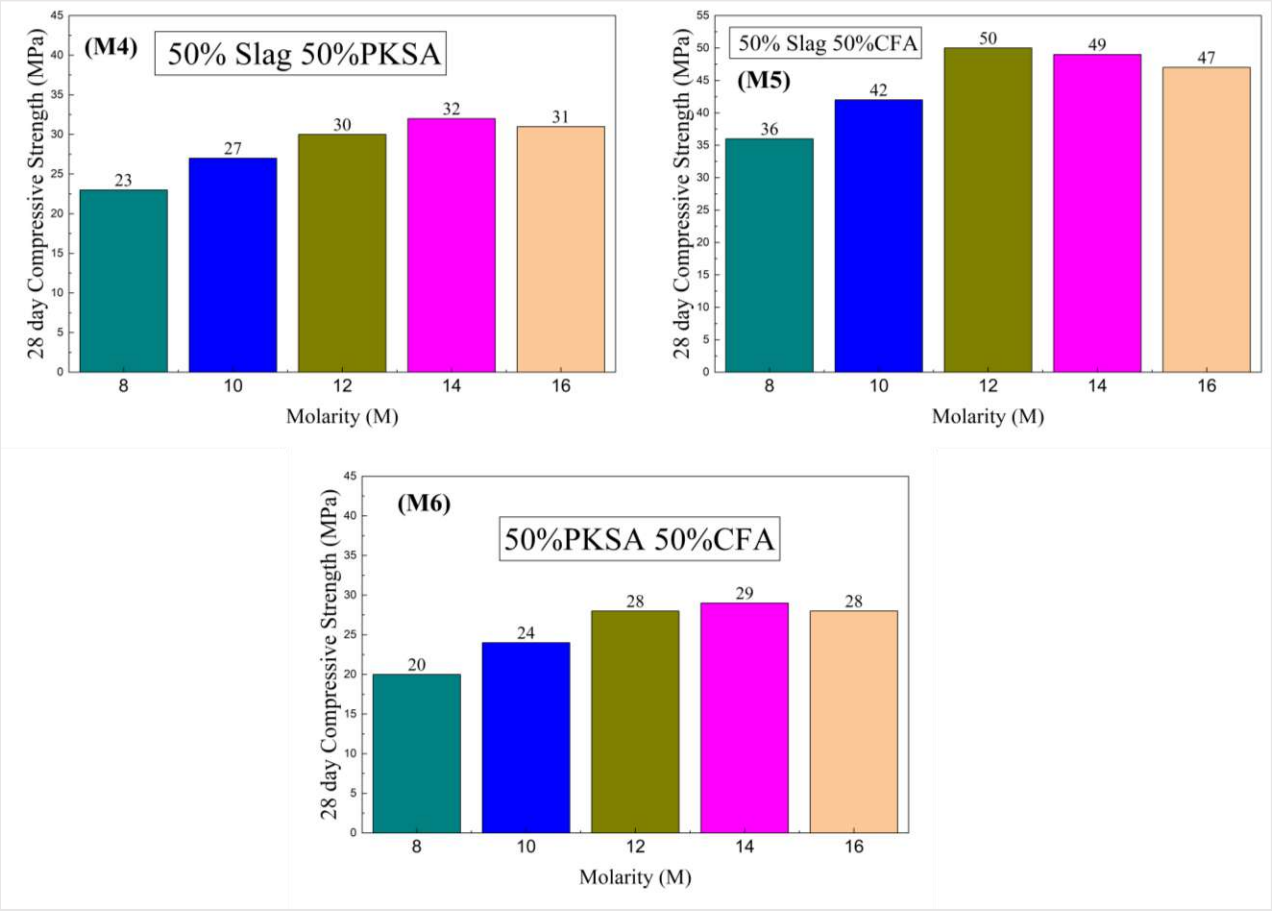

Figure 3. Single binder high calcium under Molarity

Class C fly ash (M3) mixes demonstrated moderate compressive strength (28-day 27 MPa) due to the presence of calcium in fly ash, which enables partial C–A–S–H gel formation along with N–A–S–H gels, improving the microstructural density (Ryu et al., 2015; Yip et al., 2005). Hybrid mixes such as M4 (50% Slag + 50% PKSA) exhibited improved 28-day strength (30 MPa) due to co-gel formation, where the high calcium content from slag enhances C–A–S–H formation and PKSA contributes reactive silica, increasing crosslinking in the gel network. M5 (50% Slag + 50% CFA) achieved the highest experimental results 28-day compressive strength (50 MPa), reflecting the optimal synergy between high-Ca slag and Class C fly ash. Although high NaOH molarity (14–16 M) may induce minor microcracking due to rapid gel precipitation, the densification effect predominates, consistent with observations by Škvára & Bohuněk (2021). M6 (50% PKSA + 50% CFA) showed moderate 28-day strength (28 MPa), where the presence of CFA provides sufficient calcium and aluminosilicate species to compensate for PKSA's lower reactivity.

The effect of NaOH molarity is critical: 10–12 M ensures sufficient dissolution of aluminosilicates and uniform gel polymerization, whereas 14–16 M accelerates precipitation, producing minor microstructural defects and slightly reducing maximum achievable strength (Ryu et al., 2015; Tian et al., 2021). The sand-to-binder ratio (S/B = 2) influences packing density and porosity: higher S/B ratios reduce binder content, increasing voids and lowering compressive strength. Mechanistically, the C–A–S–H/N–A–S–H co-gel network in hybrid mixes reinforces the matrix and reduces microcracks, resulting in improved compressive performance

(Chindaprasirt et al., 2012; Yip et al., 2005; Fernández-Jiménez et al., 2018).

The experimental behavior of high-calcium alkali-activated mortars varies systematically with binder composition, NaOH molarity, and curing conditions. At low molarity, the limited availability of hydroxide ions restricts the dissolution of aluminosilicates, resulting in slower formation of C–A–S–H gel and reduced early strength. Moderate molarity (10–12 M) facilitates enhanced dissolution and improved gel formation, producing a denser, more uniform microstructure that optimizes both early-age and 28-day compressive strength. At higher molarity levels (14–16 M), rapid gel precipitation can occur, sometimes leading to minor microcracking or porosity, although the overall densification of the matrix generally predominates. Binder composition strongly influences the kinetics of gel formation. Slag-rich mixes exhibit rapid C–A–S–H formation due to high calcium content, resulting in superior early strength. PKSA-rich mixes, in contrast, have lower calcium content, causing slower geopolymerization, which can be compensated by higher NaOH molarity to promote sufficient dissolution and co-gel formation. Class C fly ash contributes both calcium and silica, enhancing the formation of hybrid C–A–S–H/N–A–S–H gels that densify the matrix, although excessive alkalinity may introduce minor microstructural defects. Hybrid binders, such as 50% slag + 50% PKSA or 50% slag + 50% CFA, benefit from co-gel formation, producing a cohesive network that improves load transfer, reduces microcracking, and maximizes 28-day compressive and tensile strength.

In lower-calcium mixes, such as 50% PKSA + 50% CFA, early-age strength is slower, yet moderate molarity enables optimal hybrid gel formation over time, demonstrating the importance of balanced activator concentration and precursor chemistry. Across all systems, increasing NaOH molarity accelerates gel precipitation, which can slightly reduce early workability, yet appropriate binder ratios and controlled curing ensure maximum experimental densification and strength. Oven curing at 60 °C further enhances early-age geopolymerization by increasing ion mobility and accelerating gel crosslinking, while ambient curing allows continued slow reactions that stabilize the microstructure over 28 days. These experimental observations highlight that both precursor selection and activator chemistry must be carefully optimized to balance fresh-state workability with long-term mechanical performance. Mechanistically, the hybrid C–A–S–H/N–A–S–H gels reinforce the mortar matrix, densify the microstructure, and reduce microcracks, as confirmed in SEM and microstructural analyses of slag-rich and hybrid systems (Palomo et al., 2014; Chindaprasirt et al., 2012; Yip et al., 2005; Tian et al., 2021). The presence of sufficient calcium ensures rapid initial reaction and early strength, while reactive silica from PKSA or CFA extends gel formation, contributing to sustained 28-day strength. These results demonstrate that high-calcium alkali-activated mortars can achieve a desirable balance between workability, early reactivity, and long-term structural integrity, provided that binder composition, NaOH molarity, and curing conditions are optimized simultaneously.

3.2 Split Tensile Strength

Figure 4 illustrated the split tensite strength of alkali activated materials based mortar. The split tensile strength of the high-calcium alkali-activated mortars was experimentally determined as approximately 10–12% of the corresponding 28-day compressive strength, consistent with previous studies on high-calcium systems (Škvára & Bohuněk, 2021) .M1 (100% Slag) achieved 4.5 MPa, M2 (100% PKSA) 2.5 MPa, and M3 (100% CFA) 3 MPa. Hybrid mixes M4–M6 demonstrated higher tensile performance: M4 (50% Slag + 50% PKSA) reached 3.5 MPa, M5 (50% Slag + 50% CFA) 6 MPa, and M6 (50% PKSA + 50% CFA) 3.2 MPa. The increased tensile strength in hybrid systems is attributed to the dense C–A–S–H/N–A–S–H co-gel network, which enhances matrix cohesion, reduces microcracking, and improves load distribution.

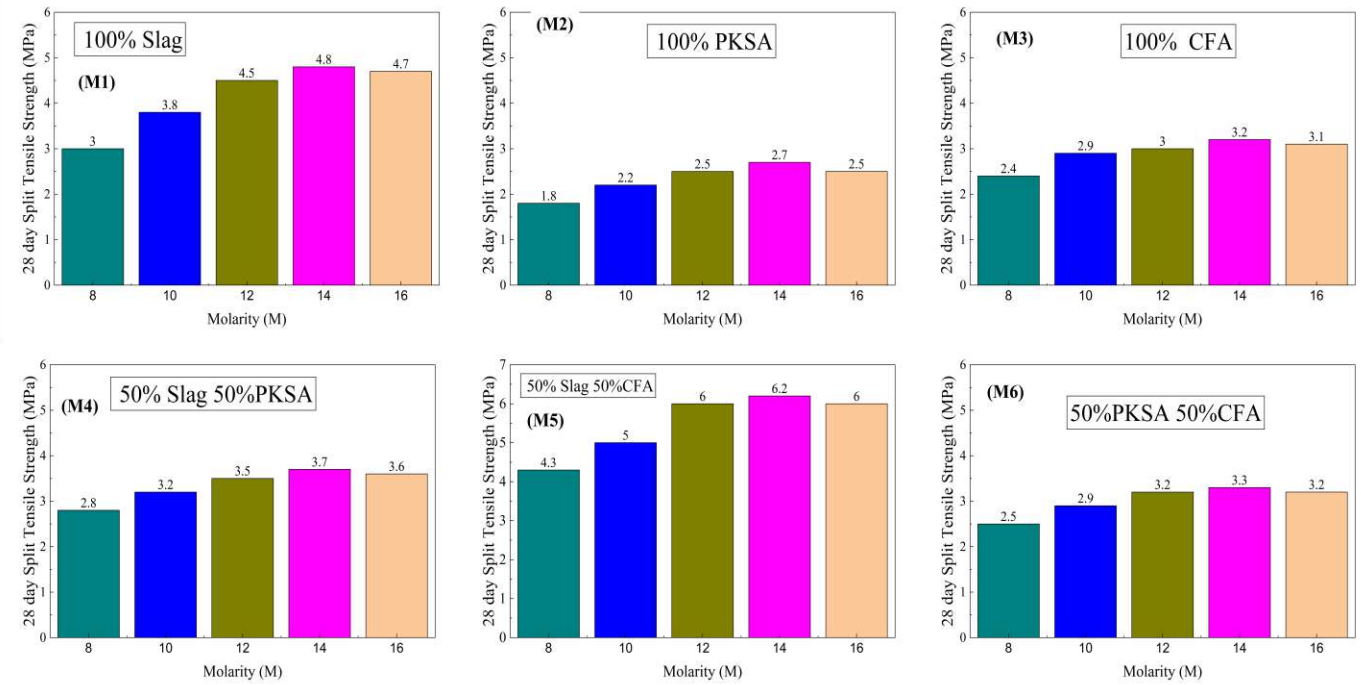

Figure 4 28 days split tensile strength of High Calcium binders

Oven curing accelerates early-age gel polymerization and densifies the matrix, improving tensile properties (Gomaa et al., 2017). Moderate NaOH molarity (10–12 M) promotes uniform gel network formation, while higher molarity (14–16 M) may cause microcracking due to rapid precipitation of gels (Tian et al., 2021). SEM and microstructural analysis in similar high-calcium systems confirm that slag-rich mixes develop a low-porosity, dense microstructure, while PKSA and CFA provide additional reactive silica for continued gel formation over 28 days (Chindaprasirt et al., 2012; Yip et al., 2005; Fernández-Jiménez et al., 2018). Mechanistically, tensile strength depends on gel continuity and interfacial bonding with sand particles. Hybrid mixes exploit the synergy of calcium from slag/CFA and silica from PKSA, producing a stronger, more cohesive matrix capable of sustaining tensile loads. These results suggest that careful selection of binder ratios, NaOH molarity, and curing regime is crucial to optimizing both compressive and tensile performance in high-calcium alkali-activated mortars.

3.3 Influence of Curing

Curing has a profound effect on the mechanical performance of high-calcium alkali-activated mortars. Oven curing at 60 °C for 5 hours accelerates the geopolymerization reactions, particularly the dissolution of aluminosilicate phases and the formation of C–A–S–H and N–A–S–H gels, resulting in higher early-age strength compared to ambient room curing (Gomaa et al., 2017; Fernández-Jiménez et al., 2018). In slag-rich mixes (M1, M5), oven curing enhances early densification of the matrix, producing up to 10–20% higher 7-day compressive strength than room-cured specimens. In contrast, PKSA-rich mixes (M2, M6) exhibit slower reaction kinetics under room temperature, as the lower calcium content delays C–A–S–H formation, leading to lower early strength (Tian et al., 2021).Although oven curing primarily boosts early-age strength, 28-day compressive and tensile strengths under ambient conditions approach the levels achieved with oven curing because the remaining unreacted aluminosilicate continues to dissolve and polymerize over time (Ryu et al., 2015). Mechanistically, higher curing temperatures

increase ion mobility, promoting faster gel nucleation and crosslinking, which reduces porosity and enhances microstructural continuity (Palomo et al., 2014). However, excessive heat or prolonged high-temperature curing may induce minor microcracking due to thermal stresses, particularly in high-alkalinity mixes (14–16 M NaOH) (Škvára & Bohuněk, 2021). Overall, proper curing is critical for optimizing both early-age and long-term mechanical performance, and hybrid mixes (slag + CFA or slag + PKSA) benefit most from controlled oven curing due to synergistic co-gel formation that densifies the mortar matrix and improves load-bearing capacity.

3.4 Mechanism of Gel Formation and Crack Development During Oven Curing

The experimental behavior of high-calcium alkali-activated mortars during oven curing can be understood in three sequential stages, which collectively govern both strength development and microstructural integrity. In the initial stage, the alkaline activator solution (NaOH + Na_2SiO_3) initiates dissolution of reactive phases in the precursors—slag, PKSA, and Class C fly ash. This process releases Ca^{2+}, SiO_4, and AlO_4 ions into the pore solution, providing the essential building blocks for geopolymer gel formation. The rate and extent of dissolution are strongly influenced by both the concentration of the alkaline activator and the temperature, with higher NaOH molarity and elevated curing temperatures accelerating ion release.

In the second stage, these dissolved species undergo polycondensation reactions, reorganizing into three-dimensional C–A–S–H (calcium-alumino-silicate hydrate) and N–A–S–H (sodium-alumino-silicate hydrate) gels. These gels interlock to form a dense co-gel network that binds fine aggregate particles together, filling capillary pores and reducing microvoids. The hybrid gel network not only enhances early-age strength but also improves the interfacial transition zone between the binder and sand, contributing to overall matrix cohesion and durability. The presence of calcium from slag and Class C fly ash accelerates early gelation, while silica from PKSA enhances long-term crosslinking and structural densification.

The third stage occurs during oven curing at 60 °C, where the elevated temperature accelerates chemical reactions, promoting rapid gel growth and early compressive strength development. However, this rapid hardening can also cause undesirable microstructural effects. Moisture evaporates from the matrix at a faster rate, resulting in shrinkage and internal stress development, which may generate fine hairline cracks. These cracks, although small, can propagate along weak points in the gel network or along the aggregate-matrix interface, potentially reducing long-term durability and tensile performance if not controlled. Thermal gradients induced by non-uniform heating may exacerbate stress concentrations, while excessive alkalinity can increase gel brittleness, further contributing to microcracking.

Overall, this three-stage mechanism illustrates the delicate balance between accelerated strength development and microstructural integrity in high-calcium alkali-activated mortars. Optimizing activator concentration, precursor blend, and curing regime is essential to maximize early strength without compromising durability. Controlled oven curing ensures rapid strength gain while minimizing the formation of microcracks, making it a practical approach for precast or repair applications. Understanding this process is crucial for designing high-performance, durable alkali-activated mortars suitable for structural and sustainable construction applications, as shown in **Figure 4**.

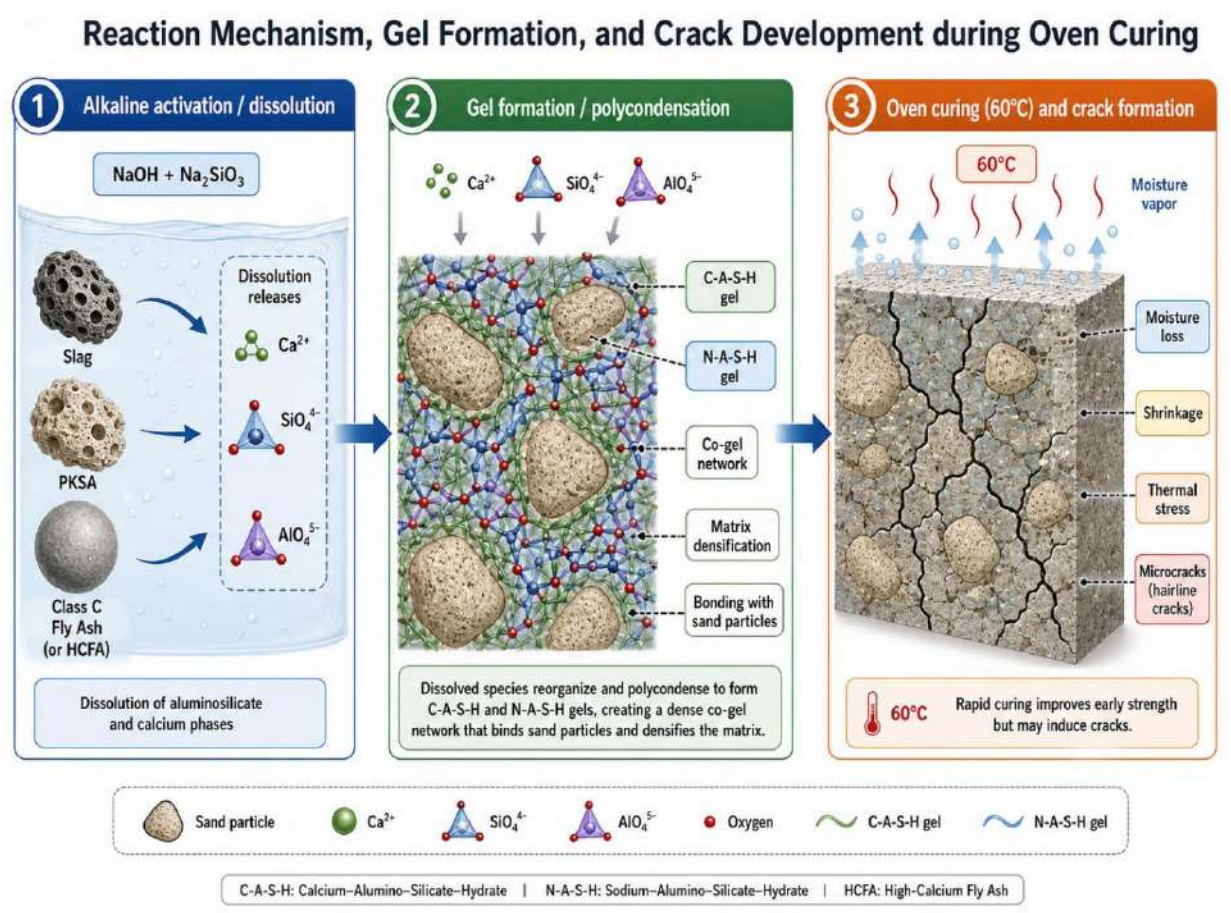

Figure 5 Schematic representation of the reaction mechanism in high-calcium alkali-activated mortars: (1) dissolution of slag, PKSA, and Class C fly ash in alkaline solution; (2) polycondensation forming C–A–S–H and N–A–S–H gels, creating a dense co-gel network; (3) oven curing at 60 °C, showing moisture loss, shrinkage, thermal stress, and microcrack formation.

4. Conclusions

1) Binder Composition Effects: 50% Slag + 50% CFA (M5) achieved the highest experiemtnal results 28-day compressive (50 MPa) and tensile (6 MPa) strengths due to the optimal synergy of high-calcium slag and Class C fly ash, forming dense hybrid C–A–S–H/N–A–S–H gels.

2) PKSA Contribution: PKSA-rich mixes (M2, M6) have lower early strength but enhance long-term gel formation due to silica contribution, improving sustainability without compromising 28-day performance.

3) NaOH Molarity: Moderate molarity (10–12 M) ensures complete aluminosilicate dissolution and uniform gel formation; excessive molarity (14–16 M) accelerates precipitation, which can produce minor microcracks.

4) Curing Effects: Oven curing at 60 °C for 5 h significantly accelerates early-age strength and microstructural densification. However, 28-day strengths converge under ambient curing due to continued slow geopolymerization.

5) Sand-to-Binder Ratio: S/B = 2 maintains optimal binder distribution and packing density; higher ratios increase porosity and reduce compressive strength.

6) Mechanistic Insight: The formation of co-gel networks (C–A–S–H/N–A–S–H) in hybrid mixes improves load transfer, reduces microcracking, and produces a cohesive, low-porosity matrix suitable for structural applications.

5. Recommendations

1) Conduct durability tests, including chloride penetration, sulfate attack, and shrinkage, to validate long-term performance of high-calcium AAM mortars.
2) Optimize activator composition (NaOH and Na_2SiO_3 ratios) for cost-effective and high-strength formulations.
3) Explore other locally available industrial and agricultural waste materials as high-calcium AAM precursors.
4) Use microstructural characterization techniques such as SEM, FTIR, and XRD to correlate gel formation with mechanical performance.
5) Investigate the effect of sand-to-binder ratio and aggregate grading on workability and mechanical properties for practical field applications.
6) Evaluate hybrid curing regimes, including partial oven and ambient curing, to optimize early-age strength while reducing energy consumption.

6. REFERENCES

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