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EFFECT OF NAOH MOLARITY ON THE MECHANICAL PROPERTIES OF CORN COB ASH-BASED GEOPOLYMER MORTAR USING LOCALLY AVAILABLE FINE AGGREGATES, A REVIEW

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Abstract

Purpose: *To review CCA-based geopolymer mortars critically and investigate the influence of NaOH molarity on mechanical and durability properties with respect to potential applications in sustainable construction in developing countries like Pakistan.*

Design/methodology/approach: *Comprehensive literature review with focus on the pozzolanic activity of CCA, activation mechanism with NaOH alkalis, and impact of 8–16 M NaOH solution on physical, mechanical, and durability properties.*

Findings: *Optimal NaOH molarity is 10–12 M, but the number of systematic investigations with 100% CCA-based binder systems is limited. Most significant research gap – no studies investigating the use of locally available fine aggregates, which is important for Pakistan.*

Research limitations/implications: *Not enough systematic research on optimization of molarity and fine aggregate characterization, durability assessment, and life cycle assessment.*

Practical implications: *Theoretical groundwork for development of environmentally friendly and locally feasible construction materials based on agricultural waste.*

Originality/value: *Systematic review of NaOH molarity effects on geopolymer properties derived from CCA with special focus on the neglected aspect of locally available fine aggregates.*

1. Introduction

1.1 The Sustainability Imperative in Construction

The construction industry is one of the largest consumers of natural resources and a major contributor to global greenhouse gas emissions. Annually, approximately 4.1 billion metric tons of ordinary Portland cement (OPC) are produced worldwide [1]. OPC manufacturing is energy-intensive and chemically emissive: the calcination of limestone ($CaCO_3 \rightarrow CaO + CO_2$) alone accounts for approximately 50–60% of the total CO_2 emissions, while the combustion of fossil fuels to reach kiln temperatures of ~1450°C contributes the remainder[2]. Overall, OPC production is responsible for 7–10% of global anthropogenic CO_2 emissions a figure comparable to the emissions of the entire European Union[3], [4] .

Climate change mitigation strategies in the construction sector have therefore focused on three main approaches: (i) improving the energy efficiency of cement plants, (ii) capturing and storing CO_2 emissions, and (iii) developing alternative binders that can partially or fully replace OPC. Among these, the development of alternative binders particularly geopolymers and alkali-activated materials has gained substantial research attention over the past two decades [5].

Geopolymers are inorganic amorphous polymers formed by the reaction of an aluminosilicate precursor (e.g., fly ash, metakaolin, slag, or agricultural ashes) with an alkaline activator solution (typically a combination of sodium hydroxide and sodium silicate). The resulting three-dimensional network of SiO_4 and AlO_4 tetrahedra provides mechanical properties comparable to or even exceeding those of OPC, while reducing CO_2 emissions by 60–80% depending on the precursor and activator used [6], [7].

1.2 Agricultural Waste: A Burden or an Opportunity?

Corn (maize, Zea mays) is one of the most widely cultivated crops globally, with annual production exceeding 1.1 billion metric tons. Corn cobs constitute approximately 18–20% of the plant's dry mass, meaning that roughly 200–220 million metric tons of corn cobs are generated each year[8]. In many developing countries, these cobs are either burned in open fields (releasing CO_2, methane, black carbon, and particulate matter) or dumped in landfills, where they decompose anaerobically to produce methane a greenhouse gas 25 times more potent than CO_2 over a 100-year period [9].

However, corn cobs are not waste; they are a resource waiting to be valorized. When incinerated under controlled conditions (600–700°C), corn cobs produce an ash (corn cob ash, CCA) that is rich in amorphous silica (55–72% SiO_2) and contains significant alumina (5–12% Al_2O_3) [10]. These chemical characteristics make CCA a suitable pozzolanic material and, more importantly, a potential precursor for geopolymer synthesis. Using CCA as a binder offers a dual environmental benefit: it reduces the environmental burden of agricultural waste disposal and provides a low-carbon alternative to OPC.

1.3 The Critical Role of NaOH Molarity in Geopolymerization

The alkaline activator solution is the engine of geopolymerization. Among the various alkalis used (NaOH, KOH, Na_2SiO_3, K_2SiO_3, etc.), sodium hydroxide (NaOH) is the most common due to its low cost, wide availability, and strong alkalinity. The concentration of NaOH, expressed in molarity (M), fundamentally influences every stage of the geopolymerization process [10]:

1. **Dissolution stage:** Hydroxide ions (OH^-) attack the aluminosilicate precursor, breaking Al-O-Si and Si-O-Si bonds. Higher OH^- concentrations accelerate dissolution but can also lead to oversaturation and premature precipitation[11].
2. **Speciation (oligomerization):** The dissolved aluminate ($[Al(OH)_4]^-$) and silicate ($[SiO_2(OH)_2]^{2-}$) species form small oligomers. The distribution of these species depends strongly on pH.
3. **Polycondensation (gelation):** Oligomers link together, releasing water and forming the final geopolymer network. The kinetics of polycondensation and thus the final microstructure and mechanical properties are highly sensitive to OH^- concentration.

The relationship between NaOH molarity and geopolymer properties is non-linear and often non-monotonic [10]:

- **Low molarity (4–8 M):** Insufficient OH^- concentration leads to incomplete dissolution of the precursor. Unreacted particles remain embedded in a poorly polymerized matrix, resulting in low compressive strengths (often <15 MPa), high porosity, and poor durability.

- **Medium molarity (8–12 M):** This range generally provides an optimal balance between dissolution and polycondensation. Complete or near-complete reaction occurs with appropriate curing (elevated temperature, 60–80°C). Compressive strengths of 25–45 MPa are typical for fly ash-based geopolymers.
- **High molarity (14–20 M):** Excessively high OH^- concentrations cause very rapid dissolution and flash setting. The exothermic reaction can generate internal stresses, leading to microcracking. Moreover, the high viscosity of concentrated NaOH solutions reduces workability. After curing, excess Na^+ ions remain in the pore solution and can migrate to the surface, forming unsightly efflorescence (white carbonate deposits) [12].

However, the optimal NaOH molarity is not universal; it depends on the chemical and mineralogical composition of the precursor, particularly its Al_2O_3 content and amorphous fraction. For CCA which has lower Al_2O_3 (~8%) than fly ash (~20–30%) or metakaolin (~40%) the optimal molarity may differ. Limited studies suggest that 10–12 M is optimal for CCA-based systems, but systematic investigations using 100% CCA as the sole precursor are lacking [13].

1.4 The Local Aggregates Gap: A Barrier to Practical Adoption

One of the most significant, yet underappreciated, gaps in geopolymer research is the almost exclusive use of standardized fine aggregates. The vast majority of published studies use ASTM C778 graded sand (from Ottawa, Illinois) or ISO 679 standard sand (from Fontainebleau, France). These materials are characterized by:

- A narrow, well-defined particle size distribution
- Rounded to sub-rounded particle shapes
- Very high silica content (>99% SiO_2)
- Absence of clay, silt, or organic contaminants
- Consistent mineralogy (predominantly quartz)

While this standardization is essential for inter-laboratory reproducibility, it creates a significant disconnect between laboratory research and field applications. Real-world fine aggregates such as the alluvial sands of the Indus River system in Pakistan exhibit substantial variability in:

- **Gradation:** Local sands rarely match the precise gradation curves of standard sands. Fineness modulus can vary from 2.2 to 3.0, affecting packing density and workability[14].
- **Particle shape:** River sands are often sub-angular to angular, whereas standard sands are rounded. Angular particles increase the specific surface area, requiring more paste for the same workability, but they also improve mechanical interlocking at the aggregate-binder interface[15].
- **Mineralogy:** In addition to quartz, local sands contain feldspar (which may be susceptible to alkaline attack), mica (platy particles that can delaminate), and sometimes carbonate fragments (which may participate in the reaction)[16].
- **Surface chemistry:** Clay coatings (from silt or clay particles) can absorb alkaline activators, effectively reducing the available OH^- concentration and altering the effective NaOH molarity[17], [18], [19].

These factors can dramatically affect the performance of geopolymer mortars. For example, clay fines can adsorb up to 20–30% of the NaOH from the activator solution, leading to incomplete geopolymerization unless the mix design is adjusted [20]. Similarly, the presence of reactive minerals (e.g., carbonates) can accelerate setting or alter the reaction products.

To date, **no published study** has systematically evaluated CCA-based geopolymer mortars using locally sourced fine aggregates from Pakistan. This gap represents a major barrier to technology transfer and practical adoption in regions where both agricultural waste (corn cobs) and construction needs are high.

1.5 Scope and Objectives of This Review

This comprehensive review aims to:

1. **Synthesize** existing knowledge on the production, characterization, and reactivity of corn cob ash as a geopolymer precursor.
2. **Analyze** the influence of NaOH molarity on the mechanical properties (compressive strength, flexural strength) and durability properties (water

absorption, porosity, efflorescence, acid/sulfate resistance, drying shrinkage) of CCA-based geopolymers.

3. **Critically assess** the state of research on the use of locally sourced fine aggregates in geopolymer systems, with special reference to the Pakistani context.
4. **Identify** key research gaps that limit the practical adoption of CCA geopolymers.
5. **Propose** future research directions, including systematic experimental studies that directly address the identified gaps.
6. **Provide** a theoretical and methodological foundation for the experimental study proposed in the accompanying Independent Research Study (IRS).

The review is structured as follows: Section 2 presents a detailed characterization of CCA, including production parameters, chemical composition, pozzolanic activity, and comparison with other agricultural ashes. Section 3 explains the chemistry of geopolymerization and the specific role of NaOH molarity. Section 4 reviews the mechanical properties of CCA-based geopolymers. Section 5 covers durability-related properties. Section 6 focuses on the critical issue of local fine aggregates. Section 7 identifies research gaps and proposes future directions. Section 8 concludes the review.#

2. Corn Cob Ash: Characterization and Pozzolanic Properties

2.1 Production Parameters and Their Influence on Ash Quality

The properties of corn cob ash are not intrinsic; they depend heavily on the production process, particularly the incineration temperature, duration, and post-incineration handling. Uncontrolled burning (e.g., open field burning) typically produces ash with:

- High residual carbon content (loss on ignition, LOI >15%)
- Significant crystalline silica phases (cristobalite, tridymite)
- Variable and unpredictable reactivity

Controlled incineration, on the other hand, can yield a highly reactive amorphous ash. The optimal temperature range is **600–700°C** [21]. Below 500°C, organic matter is incompletely combusted, leaving char that absorbs water and reduces workability[22]. Above 800°C, the amorphous silica begins to crystallize into cristobalite or tridymite, which are substantially less reactive in alkaline environments[19], [23]. The incineration time is typically 2–4 hours; longer durations risk crystallization without additional benefit.

Rapid cooling (quenching) after incineration is also important. Slow cooling allows more time for crystallization, whereas rapid cooling "freezes" the amorphous structure. Some researchers have reported that water quenching (plunging hot ash into water) produces higher reactivity than air cooling [24].

Post-incineration grinding is equally critical. Raw CCA particles are often porous, irregular, and relatively coarse (mean particle size 100–300 µm). Ball milling to a mean particle size of **<45 µm** (similar to OPC fineness) significantly increases specific surface area and reactivity. Extended grinding (60–120 minutes) can achieve mean particle sizes of 5–15 µm, further improving performance up to a point. Beyond an optimum (typically ~10 µm), agglomeration and increased water demand offset the benefits of higher surface area [25].

Table 1 summarizes the effect of production parameters on CCA quality.

Table 1. Effect of production parameters on corn cob ash properties[26].

Parameter	Suboptimal Range	Optimal Range	Effect of Deviation
Incineration temperature	<500°C or >800°C	600–700°C	<500°C: high LOI, black ash; >800°C: crystalline SiO_2, low reactivity

Parameter	Suboptimal Range	Optimal Range	Effect of Deviation
Incineration duration	<1 h or >6 h	2–4 h	<1 h: incomplete combustion; >6 h: unnecessary energy use, possible crystallization
Cooling method	Slow air cooling	Rapid (water quenching)	Slow cooling: promotes crystallization; quenching: preserves amorphous structure
Mean particle size	>100 µm	<45 µm (optimal 10–30 µm)	Coarse: low reactivity, unreacted cores; too fine (<5 µm): agglomeration, high water demand

2.2 Chemical and Mineralogical Composition

The chemical composition of CCA varies depending on corn variety, soil conditions, fertilizer use, and incineration parameters. However, a general range can be established from multiple studies [7,8,17,18].

Table 2. Typical chemical composition of corn cob ash (wt%, on a dry basis)[26].

Component	Range (wt%)	Typical Value	Role in Geopolymerization
SiO_2	55–72	65	Primary network former; provides silicate tetrahedra
Al_2O_3	5–12	8	Cross-linking agent; provides aluminate tetrahedra
Fe_2O_3	2–6	4	Minor role; can substitute for Al in some conditions
CaO	1–4	2	Can accelerate setting; may form C-S-H alongside geopolymer
MgO	1–3	2	Minor influence on reactivity
K_2O	6–15	10	Contributes to total alkalinity; can cause efflorescence
Na_2O	0.1–1	0.5	Minor; often negligible compared to added NaOH
SO_3	0.5–2	1	Can contribute to efflorescence; minor effect on strength

Component	Range (wt%)	Typical Value	Role in Geopolymerization
Loss on Ignition (LOI)	2–8	5	Unburnt carbon; high LOI reduces workability and strength

The key limitation of CCA for geopolymerization is its relatively low Al_2O_3 content (~8%) compared to conventional precursors:

- Class F fly ash: 20–30% Al_2O_3
- Class C fly ash: 15–25% Al_2O_3
- Metakaolin: 35–45% Al_2O_3
- Ground granulated blast furnace slag (GGBFS): 10–15% Al_2O_3

Alumina is essential for geopolymer cross-linking because each AlO_4 tetrahedron carries a negative charge that must be balanced by an alkali cation (Na^+ or K^+). A low Al_2O_3 content limits the degree of cross-linking, resulting in a less dense, more porous network with lower mechanical strength[27]. This limitation can be addressed by:

- **Blending CCA with alumina-rich materials** (metakaolin, fly ash, bauxite, or even red mud)
- **Using higher NaOH molarities** to enhance Al dissolution from the available alumina
- **Incorporating limestone powder** ($CaCO_3$), which may participate in the reaction and compensate for the structural deficiency (this is a novel approach proposed in the accompanying IRS study)

Mineralogically, CCA is predominantly amorphous as evidenced by X-ray diffraction (XRD) showing a broad hump between 20° and 35° 2θ. Crystalline phases, when present, include quartz (SiO_2), cristobalite (SiO_2), sylvite (KCl), and calcite ($CaCO_3$) [19]. The amorphous content is the most important factor for geopolymerization; values above 70% are desirable[28].

2.3 Pozzolanic Activity and Its Relevance to Geopolymers

Pozzolanic activity is defined as the ability of a material to react with calcium hydroxide ($Ca(OH)_2$) in the presence of water to form calcium silicate hydrates (C-S-H) or calcium aluminate silicates[29]. It is typically measured by:

- **Strength Activity Index (SAI):** The compressive strength of a mortar containing 20–30% pozzolan (by mass of cement) is compared to a control OPC mortar at 7 and 28 days. An SAI ≥75% at 28 days indicates a good pozzolan.
- **Chapelle test:** Measures the consumption of $Ca(OH)_2$ by the pozzolan.

For CCA, reported SAI values range from **75% to 115%** at 28 days, indicating that properly processed CCA meets or exceeds the requirements for a Class N pozzolan (ASTM C618) [30]. However, pozzolanic activity which involves reaction with $Ca(OH)_2$ does **not** directly predict geopolymerization performance. In alkali-activated systems without $Ca(OH)_2$ (i.e., true geopolymers), the relevant parameter is the **dissolution rate of Si and Al** in concentrated NaOH or KOH solutions. The dissolution rate depends on:

- **Amorphous content** (higher is better)
- **Specific surface area** (higher is better, up to an optimum)
- **Particle morphology** (irregular, porous particles dissolve faster than smooth, dense ones)
- **Presence of crystalline phases** (quartz dissolves very slowly in alkaline solutions)
- **Temperature and OH^- concentration**

2.4 Comparison with Other Agricultural Waste Ashes

CCA is one of several agricultural waste ashes that have been investigated as pozzolans or geopolymer precursors. Table 3 provides a comparative overview.

Table 3. Comparison of corn cob ash (CCA) with other major agricultural waste ashes.

Property	Corn Cob Ash (CCA)	Rice Husk Ash (RHA)	Sugarcane Bagasse Ash (SCBA)	Palm Oil Fuel Ash (POFA)
Global annual production (million tons, ash basis)	~15–20	~20–25	~10–15	~5–10
SiO_2 content (%)	55–72	85–95	65–85	50–65
Al_2O_3 content (%)	5–12	0.5–3	4–10	2–8
Amorphous silica content (%)	60–80	85–95	50–75	40–60
Optimal combustion temp. (°C)	600–700	600–700	600–800	500–700
Specific surface area (m^2/g)	15–35	50–80	20–40	10–25
LOI typical (%)	2–8	2–6	3–10	5–15
Geopolymer studies (relative)	Limited	Extensive	Moderate	Limited
Main limitation for geopolymer	Low Al_2O_3	Very low Al_2O_3	Moderate Al_2O_3, variable quality	High LOI, low reactivity
Geographical availability	Worldwide (corn)	Rice-growing regions	Sugarcane regions	Southeast Asia

Data compiled from [31], [32], [33], [34], [35], [36], [37]

RHA has received the most research attention due to its exceptionally high amorphous silica content (>90%). However, RHA's very low Al_2O_3 (<3%) makes it unsuitable as a sole precursor for geopolymers; it must be blended with an alumina source. SCBA has intermediate properties but can contain significant crystalline silica depending on combustion conditions. POFA often has high LOI and requires additional processing.

CCA occupies a middle ground: its SiO_2 is high enough to be reactive, and its Al_2O_3 (~8%) is higher than RHA but lower than fly ash or metakaolin. The key advantage of CCA over RHA and SCBA is its **global availability**: corn is grown on every continent except Antarctica, in both developed and developing countries. This makes CCA a more universally accessible resource than region-specific ashes.

3. Geopolymer Chemistry and the Role of NaOH Molarity

3.1 Fundamentals of Geopolymerization

Geopolymerization is a complex, multi-stage process that transforms solid aluminosilicate precursors into a three-dimensional amorphous to semi-crystalline polymeric network. The generally accepted mechanism, proposed by Provis and van Deventer [22], consists of the following stages:

Stage 1: Dissolution (Activation) The alkaline activator (typically a concentrated solution of NaOH, KOH, or their silicates) provides a high pH environment (pH >13). Hydroxide ions (OH^-) attack the surface of the aluminosilicate precursor[38], breaking the covalent bonds in the network:

$\equiv Si\text{-}O\text{-}Si\equiv + 2\ OH^- \rightarrow 2\ \equiv Si\text{-}O^- + H_2O \equiv Si\text{-}O\text{-}Al\equiv + 2\ OH^- \rightarrow \equiv Si\text{-}O^- + \equiv Al\text{-}O^- + H_2O$

The rate of dissolution depends on:

- OH^- concentration (higher = faster, but with diminishing returns)
- Temperature (higher = faster, but may cause premature gelation)
- Precursor reactivity (amorphous > crystalline)
- Surface area (higher = faster)

Stage 2: Speciation (Oligomerization) The dissolved silicate and aluminate species do not remain as simple monomers. In alkaline solution, they form a variety of oligomers[39], including:

- Silicate monomers: $[SiO_2(OH)_2]^{2-}$ (orthosilicate), $[SiO(OH)_3]^-$
- Aluminate monomers: $[Al(OH)_4]^-$
- Dimers: $[(HO)_3Si\text{-}O\text{-}Si(OH)_3]^{2-}$
- Trimers and cyclic species

The distribution of these species is pH-dependent. At very high pH (e.g., 14–16 M NaOH), the dominant species are small monomers and dimers, which polymerize rapidly but may form a less organized network.

Stage 3: Polycondensation (Gelation) Oligomers link together through condensation reactions[40], releasing water:

$\equiv Si\text{-}O^- + HO\text{-}Si\equiv \rightarrow \equiv Si\text{-}O\text{-}Si\equiv + OH^- \equiv Si\text{-}O^- + HO\text{-}Al\equiv \rightarrow \equiv Si\text{-}O\text{-}Al\equiv + OH^-$

The resulting gel is often referred to as an "N-A-S-H" gel (sodium aluminosilicate hydrate) when NaOH is used, or "K-A-S-H" gel when KOH is used. The idealized formula is:

$M_n[\text{-}(Si\text{-}O)_2\text{-}Al\text{-}O\text{-}]_n \cdot wH_2O$

where M is an alkali cation (Na^+ or K^+) that balances the negative charge on each AlO_4 tetrahedron.

Stage 4: Hardening and Microstructure Development As polycondensation proceeds, water is expelled, the gel stiffens, and the microstructure evolves. The final product is an amorphous, nanoporous network with mechanical properties that depend on the degree of cross-linking (Si/Al ratio), pore structure, and the presence of unreacted particles[41], [42], [43].

3.2 Detailed Influence of NaOH Molarity on Each Stage

The effect of NaOH molarity is not uniform across all stages; different concentrations optimize different steps.

Low molarity (4–8 M):

- **Dissolution:** Slow and incomplete. Many precursor particles remain unreacted, acting as weak inclusions or pores after leaching.
- **Speciation:** The pH is insufficient to maintain high concentrations of aluminate species; some Al may precipitate as $Al(OH)_3$ before incorporation into the network.
- **Polycondensation:** Slow kinetics; the gel that forms is poorly cross-linked with a low Si/Al ratio.
- **Resulting properties:** Low compressive strength (<15 MPa), high porosity, poor durability. However, workability is good, and efflorescence is minimal.

Medium molarity (8–12 M):

- **Dissolution:** Sufficiently rapid to dissolve most or all of the amorphous fraction within a reasonable time (24–72 h at 60–80°C).
- **Speciation:** A balanced distribution of monomers and small oligomers promotes ordered network formation.
- **Polycondensation:** Optimal kinetics; the gel achieves a high degree of cross-linking.
- **Resulting properties:** Compressive strengths of 25–45 MPa (fly ash) or 25–35 MPa (100% CCA), moderate porosity, reasonable durability. Workability is acceptable.

High molarity (14–20 M):

- **Dissolution:** Extremely rapid; the precursor may dissolve completely within minutes. This can lead to a very high concentration of silicate and aluminate species in solution.
- **Speciation:** Dominated by small monomers; oligomer formation is suppressed.
- **Polycondensation:** The high monomer concentration leads to rapid, uncontrolled polymerization often described as "flash setting." The resulting gel is highly cross-linked but may be disordered, with significant shrinkage and microcracking upon drying.
- **Resulting properties:** Early strength may be high, but long-term strength can be lower due to microcracks. Workability is poor (high viscosity). Efflorescence is severe due to excess Na^+. Drying shrinkage is high.

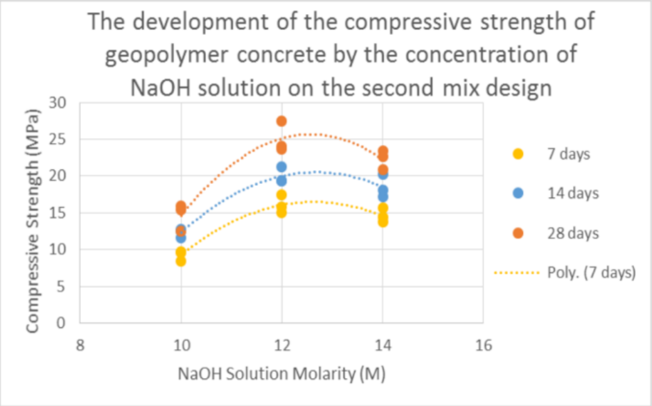

Figure 1 : strength increases with molarity up to an optimum (10–12 M for many systems), then decreases[44].

3.3 Synergy with Sodium Silicate (Na_2SiO_3)

In practical geopolymer formulations, NaOH is rarely used alone. A combination of NaOH and sodium silicate (Na_2SiO_3, commonly called "water glass") is standard because it provides several benefits:

1. **Additional soluble silica:** The geopolymer network requires a certain Si/Al ratio (typically 2–4). If the precursor has insufficient Si (which is not the case for CCA, but can be for low-Si precursors), adding Na_2SiO_3 provides the necessary Si.
2. **Improved polycondensation:** Silicate species from Na_2SiO_3 can directly participate in polycondensation without requiring precursor dissolution, accelerating gel formation.
3. **Higher final strength:** The additional silica leads to a more highly cross-linked network, increasing compressive and flexural strengths.
4. **Reduced efflorescence (potentially):** A well-balanced Na_2SiO_3:NaOH ratio can reduce the excess free Na^+ that causes efflorescence.

The activator solution is characterized by:

- **NaOH molarity** (M) – typically 8–16 M
- **Na_2SiO_3:NaOH ratio** (by mass or by volume) – typically 1.0 to 2.5
- **Modulus (Ms)** – the SiO_2:Na_2O molar ratio of the sodium silicate solution itself (typically 1.0–2.5 for commercial water glass)

For CCA-based geopolymers, the optimal Na_2SiO_3:NaOH ratio has not been systematically studied. Based on fly ash studies, a ratio of 2.0–2.5 (by mass) is common. The proposed IRS study uses a constant Na_2SiO_3:NaOH ratio (to be specified) while varying only the NaOH molarity, which is a sound experimental design.

3.4 The Issue of Efflorescence: Mechanism and Mitigation

Efflorescence is the formation of white, powdery salt deposits on the surface of geopolymers (and cementitious materials). It occurs when soluble alkali ions (Na^+, K^+) migrate with evaporating water to the surface, where they react with atmospheric CO_2 to form carbonates:

$2\ Na^+ + 2\ OH^- + CO_2 \rightarrow Na_2CO_3 + H_2O2\ K^+ + 2\ OH^- + CO_2 \rightarrow K_2CO_3 + H_2O$

Efflorescence is not only aesthetically undesirable but can also indicate a high concentration of free alkali in the pore solution, which may lead to long-term durability issues.

For CCA-based geopolymers, efflorescence risk is **higher** than for fly ash geopolymers for several reasons:

1. **High K_2O content of CCA (6–15%):** This potassium is released during dissolution and contributes to total alkalinity.
2. **Lower degree of reaction:** With only 25–35 MPa compressive strength, the reaction is less complete than in fly ash geopolymers (40–60 MPa), meaning more unbound alkali remains.
3. **Higher porosity:** Higher water absorption (8–15%) provides pathways for alkali migration.

The relationship with NaOH molarity is direct and approximately linear: higher molarity introduces more Na^+, increasing efflorescence potential. Some mitigation strategies include:

- **Using KOH instead of NaOH** to match the potassium-rich chemistry of CCA (reducing cation incompatibility) [23]
- **Adding alumina-rich materials** to consume more alkali through charge balancing
- **Reducing the Na_2SiO_3:NaOH ratio** (less free Na^+)
- **Using one-part ("just add water") geopolymer formulations** where the solid activator is less mobile
- **Surface sealing** with silane or siloxane treatments

4. Mechanical Properties of CCA-Based Geopolymers

4.1 Compressive Strength: Experimental Data and Trends

Compressive strength is the most frequently reported mechanical property for geopolymers and the primary indicator of successful geopolymerization. Table 4 summarizes key studies on CCA-based geopolymers, highlighting the range of conditions and results.

Table 4. Summary of compressive strength studies on CCA-based geopolymers.

Study	CCA Content	Activator	Curing	Compressive Strength (MPa)	Key Findings
Adesanya & Raheem [15]	100% CCA	8–12 M NaOH	Ambient, 28 d	8–15	Very low strength; ambient curing insufficient for CCA
Oluwasola et al. [16]	100% CCA	12 M NaOH + Na_2SiO_3 (2:1)	70°C, 48 h	28–42	Strength depends on CCA fineness; optimal at <45 µm
Akhtar et al. [17]	50% CCA + 50% fly ash	6–16 M NaOH + Na_2SiO_3	80°C, 24 h	Max 48 at 12 M; 38 at 14 M; 31 at 16 M	Clear optimum at 12 M; higher molarity reduces strength

Study	CCA Content	Activator	Curing	Compressive Strength (MPa)	Key Findings
Arif et al. [9]	CCA + bauxite (one-part)	Solid NaOH (8–16 M equivalent)	80°C, 48 h	22–35	Bauxite addition improves Al content; optimum at 12 M
Ramagiri & Kar [13]	100% CCA	10 M NaOH + Na_2SiO_3	60°C, 72 h	25–32	100% CCA achievable but lower than blends
Ouedraogo et al. [18]	CCA (pretreated)	12 M NaOH	80°C, 24 h	30–38	Pretreatment (acid washing) improves strength
Proposed IRS study	100% CCA & 80% CCA + 20% limestone	8–16 M NaOH + Na_2SiO_3	Intermittent (80°C, 6 h/d, 4 d)	To be determined	Novel: limestone blend + intermittent curing + local aggregates

Analysis of trends:

1. **100% CCA binders** typically achieve 25–35 MPa under optimized conditions (10–12 M NaOH, elevated temperature curing, fine grinding). This is adequate for masonry mortars, non-structural elements, pavement blocks, and low-rise construction in developing countries, but insufficient for structural concrete (which typically requires >40 MPa).
2. **Blended binders** (CCA + fly ash, CCA + metakaolin, CCA + bauxite) achieve significantly higher strengths (up to 55 MPa) because the supplementary material provides additional alumina, enabling a more highly cross-linked geopolymer network.
3. **The NaOH molarity optimum** for CCA-based systems appears to be **10–12 M**, consistent with fly ash geopolymers. However, the data are sparse: only a few studies have systematically varied molarity, and most used blended binders rather than 100% CCA.
4. **The drop at high molarity (>14 M)** is attributed to:
   - Flash setting and poor workability
   - Microcracking due to rapid heat release and subsequent drying shrinkage
   - Formation of a less ordered, more porous gel structure

4.2 Flexural Strength

Flexural strength (modulus of rupture) is important for mortars that may be subjected to bending stresses (e.g., pavement blocks, wall panels). For geopolymer mortars, flexural strength is typically **15–25%** of compressive strength, similar to OPC mortars.

For CCA-based geopolymers, reported flexural strengths range from **3–8 MPa** [24]. The ratio of flexural to compressive strength tends to increase with NaOH molarity up to the optimum (due to better matrix cohesion) and then decrease at higher molarities (due to brittleness and microcracking).

The aggregate-binder interface (interfacial transition zone, ITZ) plays a disproportionately large role in flexural strength because cracks propagate along the ITZ under tensile stresses[19]. Factors affecting ITZ quality include:

- Aggregate surface texture (rough = better bonding)
- Aggregate mineralogy (some minerals react chemically with the binder)
- Binder viscosity at the time of casting (higher viscosity may lead to poor aggregate coating)
- Drying shrinkage (which can debond the ITZ)

4.3 Factors Influencing Mechanical Performance

Beyond NaOH molarity, several other factors significantly affect the mechanical properties of CCA geopolymers.

4.3.1 Particle Size and Grinding

The fineness of CCA is one of the most important parameters. As a general rule, finer particles lead to higher strength because:

- The specific surface area increases, providing more sites for dissolution
- Unreacted cores are smaller, reducing the number of weak inclusions
- The packing density of the binder is improved

Okeke et al. [8] reported that reducing the mean particle size of CCA from 150 μm to 15 μm increased 28-day compressive strength by approximately 40% (from 22 MPa to 31 MPa). However, grinding beyond 5–10 μm leads to agglomeration and increased water demand, offsetting the benefits.

4.3.2 Blending with Supplementary Materials

Given CCA's low Al_2O_3 content, blending with alumina-rich materials is an effective strategy to improve mechanical properties. Table 5 summarizes reported improvements.

Table 5. Effect of blending on compressive strength of CCA-based geopolymers.

Blend Composition	Strength (MPa)	Improvement vs. 100% CCA	Reference
100% CCA	28–35	Baseline	[13]
70% CCA + 30% metakaolin	55	+57%	[25]
50% CCA + 50% fly ash	48	+37%	[17]
80% CCA + 20% bauxite	35	+25%	[9]
80% CCA + 20% limestone powder	?	Unknown	Proposed IRS

The proposed blend of **80% CCA + 20% limestone powder** is novel. Limestone ($CaCO_3$) is not traditionally considered a geopolymer precursor because it does not contain significant Al_2O_3. However, in the presence of alkaline activators, limestone can:

- React to form calcium (sodium) carbonate hydrates that may densify the microstructure
- Provide Ca^{2+} ions that can accelerate setting and potentially form C-S-H alongside the geopolymer gel
- Act as a microfiller, improving packing density

No systematic study of limestone powder in CCA geopolymers has been published, making this a significant research gap that the proposed IRS study aims to address.

4.3.3 Water-to-Binder Ratio (w/b)

The water-to-binder ratio affects both workability and strength. Unlike OPC, where water is primarily a mixing and hydration medium, in geopolymers the water also participates in the activator solution. Typical w/b ratios for geopolymer mortars range from 0.35 to 0.55. Lower ratios produce higher strengths but reduce workability; higher ratios improve workability but increase porosity and reduce strength.

For CCA-based mortars, the porous nature of CCA particles may require slightly higher w/b ratios (0.45–0.55) to achieve adequate workability compared to fly ash (0.40–0.50) [16].

4.3.4 Age at Testing

Geopolymers achieve most of their ultimate strength within 28 days, but the rate of strength gain depends on the precursor and curing conditions. For CCA geopolymers, 7-day strengths are typically **60–70%** of 28-day strengths, compared to 70–80% for fly ash geopolymers [13]. This slower gain suggests that CCA is less reactive and may require longer curing or higher temperatures to achieve full potential.

4.4 Comparison with OPC and Other Binders

Table 6 provides a comparative summary of mechanical and environmental performance.

Table 6. Comparative performance of CCA geopolymers vs. OPC and other binders.

Binder System	Typical 28-day Compressive Strength (MPa)	Flexural Strength (MPa)	CO_2 Emissions (kg CO_2/kg binder)	Embodied Energy (MJ/kg)	Maturity of Technology
OPC mortar (1:3)	30–50	4–8	0.85–0.95	4.5–5.5	Mature, commercial
Fly ash geopolymer mortar	40–60	5–10	0.15–0.25	1.0–2.0	Commercial (limited)
Metakaolin geopolymer mortar	35–55	4–9	0.20–0.30	1.5–2.5	Pilot scale
Slag-based alkali-activated mortar	50–70	6–12	0.20–0.35	1.5–2.5	Commercial
CCA geopolymer (optimized, 100% CCA)	25–35	3–6	0.10–0.20	0.8–1.5	Laboratory

Binder System	Typical 28-day Compressive Strength (MPa)	Flexural Strength (MPa)	CO_2 Emissions (kg CO_2/kg binder)	Embodied Energy (MJ/kg)	Maturity of Technology
CCA geopolymer (unoptimized)	8–15	1–3	0.10–0.20	0.8–1.5	Laboratory

Strength data from [13,15–18]; emissions and energy data from [1,3,26]

The key observations:

- CCA geopolymers have lower mechanical strength than fly ash or slag systems but are still adequate for many applications.
- The CO_2 emissions of CCA geopolymers are the lowest among all binders considered (excluding the energy for incineration and grinding, which is often omitted from calculations).
- The embodied energy is also low because CCA is a waste product that requires only grinding (and controlled incineration, which can use the corn cob itself as fuel).

5. Durability and Related Properties

Durability the ability of a material to resist deterioration under service conditions is as important as initial mechanical strength. For geopolymers to be adopted in practice, they must demonstrate adequate performance in terms of water transport, chemical resistance, and dimensional stability.

5.1 Water Absorption and Porosity

Water absorption is a simple but informative measure of a material's pore structure. High water absorption generally correlates with lower durability because it allows ingress of aggressive agents (chlorides, sulfates, acids)[45].

For CCA-based geopolymers, reported water absorption values range from **8–15% by weight** [27]. This is higher than:

- OPC mortars: 5–10%
- Fly ash geopolymers: 6–12%
- Metakaolin geopolymers: 7–13%

The higher absorption is attributed to:

1. **Incomplete geopolymerization** leaving unreacted CCA particles that are porous themselves
2. **Higher water demand** for workability, leading to more capillary pores after drying
3. **Particle morphology** – irregular, angular particles may not pack as densely as rounded particles

The relationship between NaOH molarity and water absorption is non-monotonic. At low molarity (8 M), absorption is high due to incomplete reaction. At optimal molarity (10–12 M), absorption reaches a minimum as the matrix densifies. At high molarity (>14 M), absorption increases again due to microcracking from shrinkage [28].

Porosity measured by mercury intrusion porosimetry (MIP) for CCA geopolymers shows:

- Total porosity: 20–35% (compared to 15–25% for fly ash geopolymers)
- Pore size distribution: Bimodal, with gel pores (<10 nm) and capillary pores (10–100 nm)

5.2 Efflorescence (Detailed Discussion)

Efflorescence is a major aesthetic and, potentially, durability concern for geopolymers. As described in Section 3.5, it results from the migration of free alkali ions to the surface.

Quantitative measurement: Efflorescence is often assessed by:

- Visual rating (0 = none, 5 = severe)
- Mass of deposit per unit area after accelerated testing (e.g., cycles of wetting and drying)
- Electrical conductivity of surface washings

For CCA geopolymers, the high K_2O content (6–15%) adds to the efflorescence potential. Some researchers have proposed that using **KOH instead of NaOH** as the activator may reduce efflorescence because the potassium from the ash and the activator are the same cation, potentially reducing ion exchange and migration [23]. However, KOH is more expensive than NaOH, limiting its practical use.

Mitigation strategies:

- **Optimize NaOH molarity** – use the minimum that achieves adequate strength (typically 10–12 M)
- **Reduce Na_2SiO_3:NaOH ratio** – less free Na^+
- **Extend curing** – more complete reaction consumes more alkali
- **Add Al-rich material** – more AlO_4 tetrahedra require more charge-balancing cations, immobilizing them in the network
- **Surface treatment** – silane/siloxane sealers can block moisture transport

6. The Critical Role of Local Fine Aggregates

6.1 Why Standardized Aggregates Are Inadequate for Technology Transfer

The overwhelming majority of geopolymer research including all studies cited in this review has used standardized fine aggregates. While this is appropriate for fundamental research, it creates a significant barrier to practical adoption because real-world aggregates differ in several critical ways. **Table 7** compares standardized sand (ASTM C778) with typical local sands from Pakistan (Indus River alluvium).

Table 7. Comparison of standardized sand vs. typical Pakistani local sand[37].

Property	**ASTM C778 Standard Sand**	**Typical Pakistani Alluvial Sand**	**Implication for Geopolymer Mortar**
Source	Ottawa, Illinois (USA)	Indus River system	Different mineralogy and geological history
Particle shape	Rounded to sub-rounded	Sub-angular to angular	Angular particles increase paste demand but improve mechanical interlocking
Fineness modulus	2.4–2.6 (controlled)	2.2–3.0 (variable)	Variable workability; may require adjustment of mix proportions
Gradation (sieve analysis)	Narrow, controlled	Broad, variable	Affects packing density and void content
Fines content (clay/silt, <75 µm)	<0.5%	2–10% (can be higher)	Fines absorb water and activator; can reduce effective alkalinity
Mineralogy (major)	>99% quartz	Quartz, feldspar, mica, carbonates (variable)	Feldspar may react with alkali (alkali-silica reaction risk); mica is platy and weak
Surface coatings	None	Clay/iron oxide coatings possible	Coatings can hinder binder-aggregate bonding

Property	ASTM C778 Standard Sand	Typical Pakistani Alluvial Sand	Implication for Geopolymer Mortar
Salt content	None	Variable (coastal areas may have chlorides/sulfates)	Salts can contribute to efflorescence and durability issues

6.2 Aggregate-Binder Interactions in Geopolymer Systems

The interfacial transition zone (ITZ) in geopolymer mortars differs significantly from that in OPC mortars. Understanding these differences is essential for predicting the performance of local aggregates.

In OPC mortars:

- The ITZ (20–50 μm from the aggregate surface) has higher porosity than the bulk paste due to the "wall effect" (cement particles cannot pack tightly against the aggregate surface).
- Oriented $Ca(OH)_2$ crystals form in the ITZ, creating a weak plane.
- Bond strength depends primarily on mechanical interlocking and van der Waals forces.

In geopolymer mortars:

- The ITZ is denser and more chemically homogeneous because the dissolved species can penetrate into the aggregate surface irregularities.
- No $Ca(OH)_2$ forms, eliminating one weakness.
- Chemical bonding can occur with certain aggregate minerals (e.g., carbonates may react to form calcium carbonate hydrates; reactive silicates may bond directly).
- However, higher drying shrinkage can cause debonding at the ITZ.

Specific considerations for local aggregates:

- **Feldspar:** Alkali feldspars (orthoclase, microcline) are susceptible to alkali-silica reaction (ASR) in high-pH environments. While ASR is well-known in OPC concrete (where the alkali source is the cement), geopolymers have even higher pH (13–14) and high alkali content. The risk of ASR with feldspar-bearing aggregates in geopolymers is **not well studied**. Some research suggests that the geopolymer gel may accommodate expansion better than OPC paste, but this is not conclusive [31].
- **Mica (biotite, muscovite):** Mica has a platy, layered structure. It can cause two problems: (i) particles may delaminate under stress, and (ii) the smooth cleavage planes may provide poor bonding with the binder. High mica content in fine aggregates is generally undesirable for any cementitious material.
- **Carbonates (limestone, dolomite):** Unlike siliceous aggregates, carbonates can participate in the reaction. In highly alkaline conditions, $CaCO_3$ may dissolve and reprecipitate as calcium carbonate hydrates or even react with the aluminosilicate gel to form calcium (sodium) alumino-carbonates. This could potentially **improve** bonding and densify the ITZ.
- **Clay coatings:** Clay minerals (kaolinite, illite, smectite) have high specific surface area and cation exchange capacity. They can absorb NaOH from the activator solution, effectively reducing the available OH^- concentration. This phenomenon has been documented in fly ash geopolymers with clay-bearing sands [14]; the effect is likely similar for CCA.

6.3 The Pakistani Context

Pakistan is an ideal case for studying the use of local aggregates in CCA geopolymers because:

1. **Corn production is significant:** Pakistan produces approximately 6–8 million metric tons of corn annually, generating ~1.2–1.6 million tons of corn cobs.
2. **Construction activity is high:** With a population exceeding 240 million, infrastructure development is a national priority.
3. **Cement CO_2 emissions are a concern:** Pakistan's cement industry emits

approximately 30–40 million tons of CO_2 annually.

4. **Local aggregates are variable:** The Indus River and its tributaries produce sands with different characteristics in different regions (Punjab, Sindh, Khyber Pakhtunkhwa, Balochistan).

Table 8. Preliminary characterization of Pakistani sands (based on field observations and limited testing)[46]

Region	Typical Fineness Modulus	Fines Content (%)	Dominant Minerals	Special Characteristics
Punjab (central)	2.5–2.8	3–7	Quartz, feldspar, mica	Generally good quality
Sindh (lower Indus)	2.2–2.6	5–10	Quartz, mica, carbonates	Higher fines; some salt contamination near coast
Khyber Pakhtunkhwa	2.6–3.0	2–5	Quartz, feldspar, amphibole	Coarser, angular particles
Balochistan	Variable	1–8	Quartz, carbonates (limestone)	Carbonate-rich in some areas

6.4 Research Gaps Related to Local Aggregates

Based on the analysis above, the following specific research gaps are identified:

1. **No data on CCA geopolymer bonding to feldspar or mica minerals** commonly found in Pakistani sands.
2. **No quantification** of the effect of fines content (clay/silt) on activator demand and effective NaOH molarity.
3. **No long-term durability studies** (6–24 months) under local environmental conditions (high summer temperatures, monsoon humidity, possible salt exposure in coastal areas).
4. **No economic analysis** comparing CCA geopolymer mortars with OPC mortars using local materials, including transportation and processing costs.
5. **No mix design guidelines** for CCA geopolymer mortars that account for local aggregate variability.

The proposed IRS study will address the first two gaps (bonding and fines effect) through systematic testing of one local sand. Subsequent studies can extend to other sands.

7. Research Gaps and Future Directions

7.1 Summary of Critical Gaps

Based on this comprehensive review, the following critical research gaps are identified:

Gap 1: Systematic NaOH molarity optimization for 100% CCA binders Most existing studies have examined CCA as a partial replacement (20–30%) in blended cements or as a component in blended geopolymers (CCA + fly ash). The behavior of 100% CCA binders particularly the optimal NaOH molarity as a function of CCA characteristics (amorphous content, particle size, K_2O content) remains inadequately characterized. Only a handful of studies have varied molarity systematically, and none have done so with the combination of local aggregates and limestone powder blending proposed here.

Gap 2: Absence of studies using locally sourced aggregates from developing countries The disconnect between laboratory research (standardized sands) and field application (local aggregates) represents a fundamental barrier to technology transfer. Without data on how CCA geopolymers perform with real-world aggregates, contractors and engineers will lack confidence to adopt the technology.

Gap 3: Lack of combined mechanical and durability characterization Studies typically report either mechanical properties (compressive/flexural strength) or durability (water absorption, efflorescence, acid resistance), but rarely both for the same material system. This makes holistic performance assessment difficult. The proposed IRS study explicitly includes both mechanical and durability testing on the same specimens.

Gap 4: No data on CCA + limestone powder blends Limestone powder, widely available and inexpensive, has shown benefits in OPC systems (as a filler and nucleation site) and in some alkali-activated systems. However, it has not been systematically evaluated in CCA geopolymers. The hybrid blend (80% CCA + 20% limestone) proposed in the IRS document represents an unexplored formulation that could potentially improve mechanical properties and reduce efflorescence.

Gap 5: Insufficient understanding of efflorescence mechanisms and mitigation for CCA systems While efflorescence is recognized as a problem, quantitative relationships between NaOH molarity, K_2O content of CCA, curing conditions, and efflorescence severity have not been established. Predictive models are lacking.

Gap 6: Intermittent curing regime The proposed intermittent curing (80°C for 6 hours/day over 4 days) has not been studied for CCA geopolymers. Its effects on strength development, microstructure, and energy efficiency are unknown.

7.2 Proposed Research Priorities

Based on the gaps identified, the following research priorities are proposed, organized by time horizon.

Immediate (0–12 months):

1. **Systematic molarity study** (8, 10, 12, 14, 16 M) for 100% CCA and 80% CCA + 20% limestone powder, using a fixed local fine aggregate source. Measure compressive strength, flexural strength, water absorption, porosity, and efflorescence at 7 and 28 days.
2. **Characterize the local aggregate** (gradation, specific gravity, absorption, fines content, mineralogy by XRD) and correlate with performance.
3. **Determine the optimal NaOH molarity** for each binder formulation and aggregate type.

Short-term (12–24 months):

4. **Develop a classification system** for local aggregates based on their performance in CCA geopolymer mortars. This would allow practitioners to predict performance without testing every aggregate source.
5. **Investigate the effect of fines content** by adding controlled amounts of clay to clean sand, quantifying the reduction in effective NaOH concentration and strength.
6. **Optimize the intermittent curing regime** (vary temperature, daily heating duration, number of cycles) to maximize strength while minimizing energy consumption.

Medium-term (24–48 months):

7. **Long-term durability studies** (6–24 months) under real environmental conditions (outdoor exposure in Pakistan's climate). Monitor strength retention, mass change, cracking, and efflorescence.
8. **Life cycle assessment (LCA)** comparing CCA geopolymer mortars with OPC mortars, including all stages: corn cob collection, transportation, incineration, grinding, activator production, mixing, curing, and end-of-life.
9. **Economic analysis** (life cycle costing) to determine the cost competitiveness of CCA geopolymers in the Pakistani market[47].

Long-term (>48 months):

10. **Demonstration projects** (e.g., paving blocks, non-structural walls, repair mortars) to build field experience and data.
11. **Development of draft code provisions** for CCA geopolymer mortars, in collaboration with the Pakistan Engineering Council and building code authorities.
12. **Capacity building** – training programs for engineers, technicians, and construction workers on the production and use of CCA geopolymers.

7.3 Practical Implementation Challenges

Even with successful research outcomes, several practical challenges must be addressed for CCA geopolymer technology to achieve real-world impact:

Supply chain development: Controlled incineration facilities for corn cobs do not currently exist in most regions of Pakistan. Developing decentralized processing capacity (e.g., small-scale kilns at agricultural collection points) is a non-trivial infrastructure challenge. However, corn cobs themselves can be used as fuel for the incineration process, potentially making it energy-neutral or even energy-positive.

Quality control:CCA composition varies with corn variety, growing conditions (soil, fertilizer, climate), and incineration parameters. Rapid, low-cost quality assessment methods (e.g., loss on ignition, simple color tests, or portable XRF) are needed for field applications. Without such methods, inconsistent CCA quality could lead to unreliable performance.

Building code acceptance: Geopolymer materials are not yet incorporated into most national building codes, including those of Pakistan. Demonstration projects and code development efforts are needed. This requires collaboration between researchers, the Pakistan Engineering Council, and international bodies like ASTM and RILEM.

Training and knowledge transfer: Construction workers and engineers familiar with OPC technology require training on geopolymer mixing, handling, and quality control procedures. Geopolymer mortars have different rheology (often more thixotropic), different setting behavior (can be very rapid with high molarity), and different curing requirements (heat curing is often needed). Training materials and workshops will be essential.

Perception and acceptance:"Ash" and "waste" have negative connotations for some stakeholders. Educating contractors, government officials, and the public about the safety, performance, and environmental benefits of CCA geopolymers will be important for adoption.

8. Conclusion

This comprehensive review has synthesized the current state of knowledge on corn cob ash-based geopolymer mortars, with a particular focus on the influence of NaOH molarity and the critical but understudied role of locally available fine aggregates.

The following key conclusions are drawn:

1. **CCA is a viable geopolymer precursor** when properly processed. Controlled incineration at 600–700°C followed by grinding to <45 µm yields an ash with 55–72% amorphous SiO_2 and 5–12% Al_2O_3. While the Al_2O_3 content is lower than conventional precursors (fly ash, metakaolin), optimized formulations can achieve compressive strengths of 25–35 MPa adequate for many non-structural and semi-structural applications.
2. **NaOH molarity is a critical parameter** that affects dissolution, polycondensation, microstructure, and durability. Based on limited available data, an optimal molarity of **10–12 M** is indicated for CCA-based geopolymers. Higher molarities (>14 M) lead to flash setting, microcracking, reduced strength, and severe efflorescence. Lower molarities (<8 M) result in incomplete reaction and low strength.
3. **The use of standardized fine aggregates in nearly all published studies** represents a significant gap that hinders technology transfer. Real-world aggregates such as the alluvial sands of Pakistan differ in gradation, particle shape, mineralogy, and fines content. These differences can substantially affect activator demand, workability, ITZ bonding, and long-term durability. **No published study has evaluated**

CCA geopolymer mortars with South Asian alluvial sands.

4. **Durability properties** (water absorption, efflorescence, acid resistance, drying shrinkage) are influenced by NaOH molarity and precursor composition. CCA geopolymers generally have higher water absorption (8–15%) and efflorescence potential than fly ash geopolymers, but better acid resistance than OPC. Mitigation strategies include optimizing molarity, blending with Al-rich materials, and using KOH instead of NaOH.

5. **The proposed experimental study** (varying NaOH molarity from 8–16 M, testing mechanical and durability properties, using local Pakistani aggregates, and including limestone powder blends) directly addresses multiple identified research gaps. The novel elements limestone blending, intermittent curing, and the use of local aggregates have the potential to advance the field significantly.

6. **Future research priorities** include systematic molarity optimization for 100% CCA, classification of local aggregates, long-term durability testing under real environmental conditions, life cycle assessment, and demonstration projects. Practical challenges (supply chain, quality control, code acceptance, training) must also be addressed.

The successful development of CCA-based geopolymer mortars using locally available materials would provide a sustainable, low-cost, low-carbon construction option for Pakistan and other corn-growing regions of the developing world. Given the urgent need to reduce cement-related CO_2 emissions and the pressing problem of agricultural waste management, this research direction is both timely and impactful.

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