A Comprehensive Review on Geopolymer Bricks: Raw Materials, Synthesis, Mechanical Properties, Durability, and Sustainability

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Abstract—

The construction industry accounts for a substantial share of global CO_2 emissions, with conventional clay and cement-based bricks being among the primary contributors. In response, geopolymer bricks have emerged as a structurally capable and environmentally responsible alternative, synthesized through the alkali activation of aluminosilicate precursors such as fly ash, ground granulated blast furnace slag (GGBS), metakaolin, and rice husk ash. This review consolidates findings from 45 open-access research studies, primarily from Elsevier and allied journals, published between 2016 and 2026. The paper examines the fundamental chemistry of geopolymerization, the roles of key precursor materials and alkaline activators, and the influence of mix design variables including molarity, silicate-to-hydroxide ratio, curing temperature, and curing duration on the compressive strength, water absorption, flexural strength, and microstructural behavior of geopolymer bricks. Durability characteristics — covering resistance to sulfate attack, acid exposure, chloride penetration, and elevated temperatures — are critically reviewed. Life cycle assessment data consistently demonstrate CO_2 emission reductions of 43–80% compared to ordinary Portland cement bricks. Challenges related to scale-up, cost competitiveness, and standardization are discussed, and a forward-looking future scope aligned with current research gaps is presented.

Keywords— Geopolymer bricks; Fly ash; Alkali activation; Compressive strength; Durability; Life cycle assessment; Sustainable construction.

I. INTRODUCTION

Brick manufacture has a history spanning thousands of years, yet the production methods employed today continue to carry a significant environmental burden. Conventional fired clay bricks require kiln temperatures exceeding 900°C and consume large tracts of fertile topsoil — an estimated 2,200 m^3 of soil per billion bricks produced annually. At the global scale, the burnt brick sector is responsible for approximately 360 billion bricks per year, consuming 15,500 hectares of land and releasing uncontrolled pollutants into the atmosphere. Cement-based bricks, while alleviating topsoil depletion, still rely heavily on ordinary Portland cement (OPC), whose production generates nearly 0.8–0.9 tons of CO_2 per ton of clinker.

These environmental realities have driven considerable academic and industrial interest in alkali-activated materials (AAMs) and geopolymers as cement-free, kiln-free alternatives. Coined by the French scientist Joseph Davidovits in 1978, the term "geopolymer" describes an inorganic alumino-silicate polymer formed through the alkaline activation of alumino-silicate source materials — a reaction that proceeds at ambient or mildly elevated temperatures and requires no energy-intensive clinkering. When applied to brick production, geopolymerization offers the dual advantage of valorizing industrial by-products — particularly fly ash from coal-fired power plants — while delivering products whose compressive strength, durability, and fire resistance can match or exceed those of conventional bricks. [1,2,3]

India alone generates approximately 120 million tons of fly ash annually from 260 million tones of coal combustion, and this stockpile covers nearly 15,000 hectares of useable land. Converting even a fraction of this industrial waste into geopolymer bricks represents a compelling circular economy opportunity. [5] Beyond fly ash, researchers have explored GGBS, metakaolin, red mud, rice husk ash, ceramic waste, construction and demolition waste (CDW), and agricultural residue ashes as geopolymer precursors, expanding the material palette considerably. [25]

Despite the growing body of research, geopolymer bricks have not yet achieved widespread commercial deployment. Key barriers include the variability of precursor chemistry, the corrosive nature of alkaline activators, the lack of harmonized testing standards, and questions around large-scale cost-effectiveness. This review addresses these issues comprehensively, drawing on 45 peer-reviewed, open-access studies from Elsevier, MDPI, Springer Nature, Nature Scientific Reports, and allied publishers.

II. LITERATURE REVIEW

Numerous studies have explored the use of industrial waste materials in geopolymer brick production. Researchers have demonstrated that fly ash-based geopolymer bricks exhibit high compressive strength and durability. The inclusion of GGBS has been found to enhance early strength and reduce curing time. Previous studies indicate that geopolymer bricks can achieve compressive strengths ranging from 7 MPa to 25 MPa depending on mix proportions and curing conditions. Water absorption values are generally lower than conventional bricks, indicating improved durability. Additionally, studies have highlighted the superior resistance of geopolymer bricks to sulphate attack, acid exposure, and thermal variations. However, some limitations have been identified, including variability in raw material properties, lack of standard codes, and challenges in large-scale production. This review builds upon existing research by consolidating findings and emphasizing sustainability aspects such as CO_2 reduction and waste utilization.

III. METHODOLOGY

I. GEOPOLYMERIZATION: FUNDAMENTAL CHEMISTRY AND REACTION MECHANISM

A. The Geopolymerization Process

Geopolymerization is a polycondensation reaction between an alumino-silicate source and a highly alkaline activator solution. The reaction proceeds

in three broad stages: dissolution, reorientation, and polymerization. In the dissolution stage, OH^- ions from the activator attack Si–O–Si and Si–O–Al bonds in the alumino-silicate network, liberating reactive Al^{3+} and Si^{4+} species into solution. These species then reorganize into alumino-silicate monomers — primarily SiO_4 and AlO_4 tetrahedra — which condense to form oligomers. Ultimately, a three-dimensional amorphous to semi-crystalline alumino-silicate gel network develops, giving the geopolymer its binding and structural properties. [1,2,3]

The substitution of Si^{4+} by Al^{3+} in the tetrahedral framework creates a charge imbalance that is neutralized by alkali cations (Na^+ or K^+) from the activator, forming charge-balanced, zeolite-like structural units. [2] The overall Si/Al ratio of the system governs the nature of the resulting polymer: ratios of approximately 1–2 typically yield polysialate and polysialate-siloxo networks with excellent mechanical performance, while higher Si/Al ratios promote more silicate-rich frameworks with reduced crosslink density. [2]

B. Structural Units and Network Formation

The products of geopolymerization are commonly designated based on the dominant structural repeat unit. Poly(sialate) with Si/Al ≈ 1 yields a rigid, densely crosslinked network. Poly(sialate-siloxo) with Si/Al ≈ 2 balances strength and workability. Poly(sialate-disiloxo) with Si/Al ≈ 3 is used in high-temperature applications. Research confirms that geopolymers with Si/Al ratios between 1.5 and 2.0 consistently achieve the highest compressive strengths across a range of precursor types and activator systems. [11,16]

II. RAW MATERIALS FOR GEOPOLYMER BRICKS

A. Fly Ash

Fly ash (FA) is by far the most extensively studied precursor for geopolymer bricks. As a by-product of coal combustion, FA is abundantly available and rich in amorphous silica and alumina — typically 40–60% SiO_2 and 20–30% Al_2O_3 — making it highly reactive in alkaline environments. [7,9] Class F fly ash (low calcium, from bituminous coal) is particularly preferred for geopolymer synthesis because its low CaO content prevents rapid uncontrolled setting. Studies report compressive strengths ranging from 10 MPa to over 50 MPa for FA-based geopolymer bricks, depending on mix design and curing regime. [4,5]

B. Ground Granulated Blast Furnace Slag (GGBS)

GGBS is a calcium-rich by-product of pig iron manufacture. Its inclusion in geopolymer mixes accelerates setting and significantly improves early-age compressive strength, owing to the formation of calcium silicate hydrate (C-S-H) alongside the alumino-silicate geopolymer gel. The optimal GGBS-to-FA replacement level is typically between 20% and 40%, beyond which rapid stiffening can impair workability and final uniformity. [5,11]

C. Metakaolin

Metakaolin (MK) is produced by calcining kaolin clay at 600–900°C to dehydroxylate its layered crystal structure, yielding a highly reactive amorphous alumino-silicate. While more expensive than FA or GGBS, MK produces geopolymers with superior whiteness, lower density, and excellent chemical resistance. Kaolin-based geopolymer bricks activated with combined NaOH and Na_2SiO_3 solutions exhibit significantly higher compressive strength than those activated with NaOH alone. [38]

D. Rice Husk Ash and Agro-Residue Ashes

Agricultural residue ashes — including rice husk ash (RHA), sugarcane bagasse ash (SCBA), and cow dung ash (CDA) — are gaining research attention as low-cost, regionally available supplementary precursors. The silica content of RHA (85–95% SiO_2) makes it a viable activator supplement, reducing dependence on commercial sodium silicate solutions.

E. Construction and Demolition Waste

Recycled concrete powder (RCP) and recycled brick powder (RBP) have been demonstrated as viable geopolymer precursors. Geopolymeric brick samples produced from recycled concrete powder and recycled brick powder combined with an alkaline solution achieved a maximum compressive strength of 59.53 MPa — a result that increased consistently with higher RCP content. [14]

F. Other Precursors

Red mud (bauxite processing waste), ferrosilicon slag, ceramic dust, and palm oil fuel ash (POFA) have all been tested as sole or supplementary geopolymer precursors. Each brings specific chemical advantages (e.g., the high Fe_2O_3 content of red mud strengthens the matrix), but may also introduce heavy metals or require pretreatment for acceptable performance.

III. ALKALINE ACTIVATORS AND MIX DESIGN PARAMETERS

A. Types of Alkaline Activators

The two most widely employed activators are sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3, commonly called water glass). NaOH provides the hydroxide ions needed for dissolution, while Na_2SiO_3 supplies additional soluble silica that promotes polymerization into a denser, higher-strength matrix. Potassium hydroxide (KOH) and potassium silicate (K_2SiO_3) have also been studied, offering slightly different reaction kinetics and product microstructures. During mixing, a mass ratio of Na_2SiO_3 to NaOH of 2.5 is commonly maintained to balance workability, setting time, and compressive strength development. [5,11]

B. Effect of NaOH Molarity

NaOH concentration (molarity) is one of the most influential mix parameters. Higher molarities (8M–16M) generally dissolve more silica and alumina from the precursor, increasing the availability of reactive species for polymerization. Studies on fly ash and GGBS bricks found that 12M to 16M NaOH produced optimal compressive strength when combined with a Na_2SiO_3/NaOH ratio of 2.5 and ambient curing, while at lower molarities (4–8M), elevated curing temperatures of 40–80°C were required to achieve comparable strength. [5,11]

C. Silicate Modulus and Si/Al Ratio

The silicate modulus (Ms = SiO_2/Na_2O molar ratio in the Na_2SiO_3 solution) typically ranges from 1.0 to 3.0. Research indicates that Ms values between 1.5 and 2.5 yield the highest compressive strengths for fly ash-based systems. [11] Si/Al ratios of 1.5–2.0 consistently produce the densest networks and the highest strengths. [11,16]

D. Liquid-to-Solid Ratio

The liquid-to-solid (L/S) ratio influences both workability and porosity. Lower L/S ratios (0.35–0.45) produce denser, stronger bricks but reduce workability, while higher ratios improve flowability at the expense of compressive strength. An optimal L/S of 0.40 is commonly reported for fly ash-GGBS binary systems in brick applications. [5]

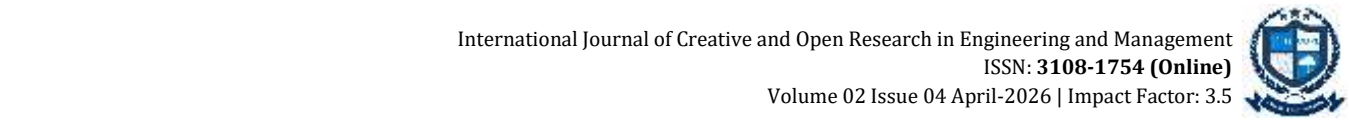
IV. CURING CONDITIONS AND THEIR INFLUENCE ON PROPERTIES

A. Curing Temperature

Curing temperature is a critical parameter for low-calcium (Class F fly ash) geopolymer systems, where ambient temperatures alone may be insufficient to drive full geopolymerization. High moderate temperatures between 80 and 90°C induce higher compressive strengths in geopolymers because elevated temperature favors the geopolymerization process. [30] Elevated curing at 60–80°C for 24–72 hours is commonly employed for fly ash-dominant mixes. [5,7] For binary systems containing GGBS or MK, ambient curing at 25–30°C for 28 days often achieves adequate strength. [5,11]

C. Relative Humidity

Moisture retention during curing is essential to maintain the alkaline environment needed for ongoing polycondensation. Research indicates



that an RH of 70% was the most effective in increasing mechanical strength, whereas pastes cured at 30% and 90% RH exhibited the lowest strength, suggesting that both low and high levels of moisture during curing are suboptimal for alkali-activated material systems. [16]

V. MECHANICAL PROPERTIES OF GEOPOLYMER BRICKS

A. Compressive Strength

Compressive strength is the primary structural benchmark for bricks. Geopolymer bricks derived from fly ash, GGBS, and metakaolin have achieved compressive strengths ranging from 8 MPa to over 60 MPa — well above the minimum requirements of most national standards, including IS 1077 (India) and ASTM C62. [14,25] Bricks with an optimal mix of 20–30% clay and 70–80% fly ash achieved a compressive strength of up to 32.5 MPa, satisfying ASTM C62 requirements for severe weathering conditions. [15] Relative to fired clay units, these geopolymer bricks delivered up to 91% higher compressive strength and 56.5% higher modulus of rupture. [17]

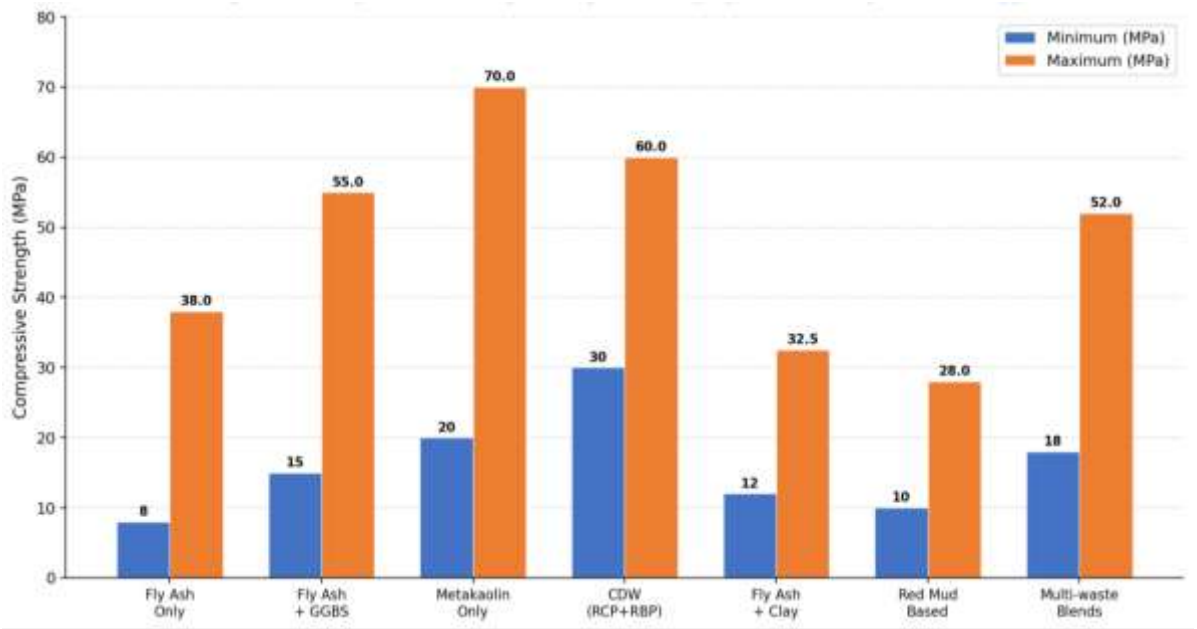
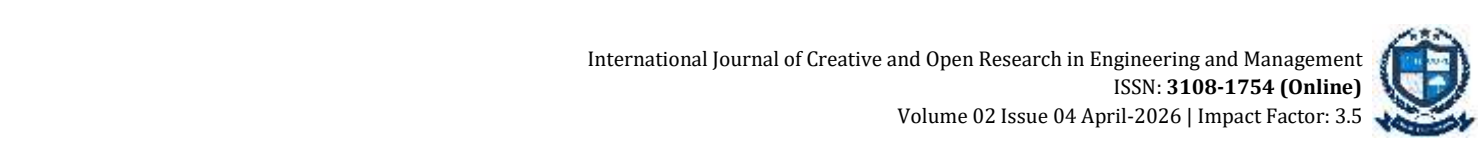


Figure 1: Compressive Strength Ranges of Geopolymer Bricks by Precursor Type (Sources: [4, 5, 14, 17, 25, 30])

Table I: Summary of Compressive Strength Data

Precursor System	Min Strength (MPa)	Max Strength (MPa)
Fly Ash Only	8	38
Fly Ash + GGBS	15	55
Metakaolin Only	20	70
CDW (RCP + RBP)	30	60
Fly Ash + Clay	12	32.5
Red Mud Based	10	28
Multi-waste Blends	18	52



B. Flexural and Tensile Strength

Flexural strength and splitting tensile strength are critical for bricks used in load-bearing masonry. Geopolymer bricks generally achieve flexural strengths of 3–8 MPa, which are comparable to or higher than conventional fired clay bricks. [17,25]

The incorporation of fibers — polypropylene, basalt, or PVA — at 1–1.5% by volume has been shown to substantially enhance flexural performance and post-crack ductility, addressing the inherent brittleness of geopolymer matrices. [27,43]

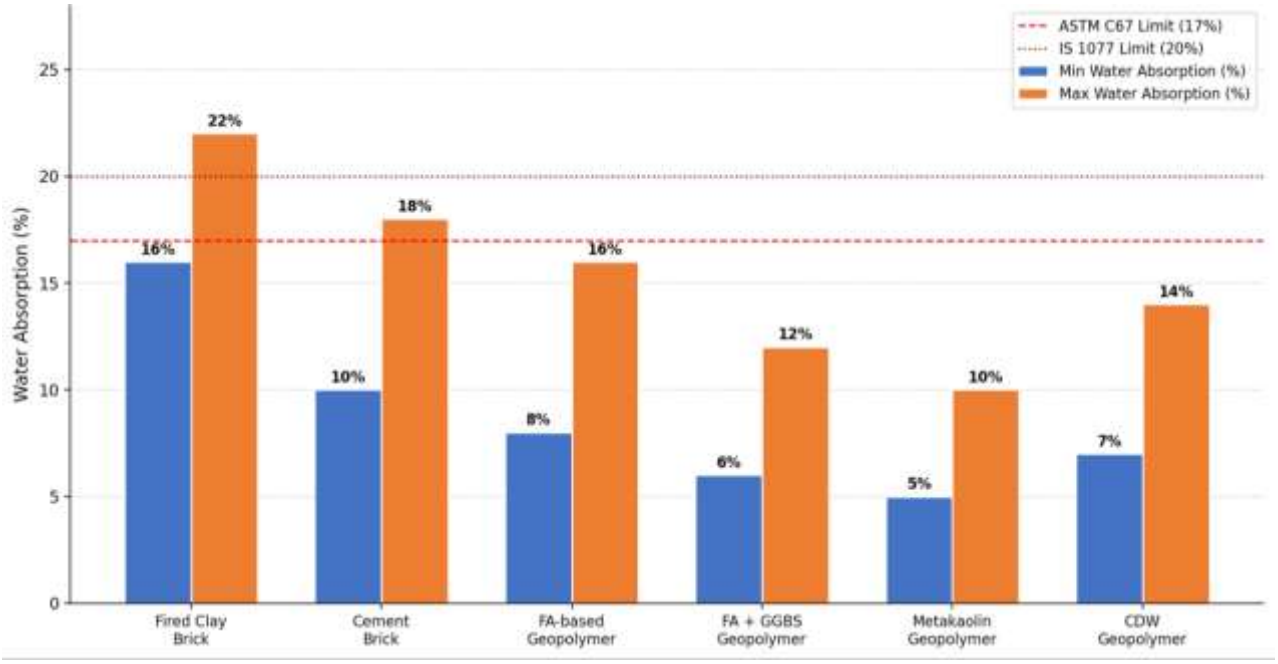


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Table II: Water Absorption Range of Geopolymer Bricks vs Conventional Bricks

Brick Type	Min WA (%)	Max WA (%)
Fired Clay Brick	16	22
Cement Brick	10	18
FA-based Geopolymer	8	16
FA + GGBS Geopolymer	6	12
Metakaolin Geopolymer	5	10
CDW Geopolymer	7	14

C. Water Absorption

Water absorption is a durability proxy and a key quality criterion for bricks. IS 1077 and ASTM C67 impose water absorption limits of ≤20% and ≤17% by weight, respectively. Geopolymer bricks based on optimized FA-GGBS systems typically exhibit water absorption of 8–16%, comfortably within standard thresholds. [20,25] Relative to fired clay units, geopolymer masonry bricks exhibited 6–29% lower water absorption, attributed to the dense N-A-S-H gel matrix with reduced porosity confirmed by SEM analysis. [17]

VII. MICROSTRUCTURAL CHARACTERIZATION

A. Scanning Electron Microscopy (SEM)

SEM analysis is the standard microstructural tool for geopolymers. Well-reacted FA-based geopolymers display a dense, homogenous matrix with unreacted spherical fly ash particles embedded within the gel. Increasing NaOH molarity and curing temperature reduces the number of unreacted particles and increases gel connectivity, which correlates with higher compressive strength. SEM analysis of optimized geopolymer bricks confirmed a dense N-A-S-H gel matrix with reduced porosity compared to fired clay equivalents, explaining their superior mechanical and durability performance. [17]

B. X-ray Diffraction (XRD)

XRD analysis of geopolymer bricks reveals a broad amorphous hump in the 20–35° 2θ region, characteristic of the alumino-silicate gel phase. Crystalline phases such as mullite and quartz from the original fly ash remain largely unreacted and are visible as sharp peaks superimposed on the amorphous background. Higher curing temperatures shift this hump toward greater 2θ values, indicating denser, more ordered gel networks. [9]

C. Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR spectra of geopolymers display a dominant Si–O–T (T = Si or Al) asymmetric stretching band near 950–1020 cm^{-1}. As geopolymerization proceeds, this band shifts to lower wavenumbers, reflecting the progressive incorporation of Al into the silicate framework and the formation of the three-dimensional geopolymer network. Comparing raw fly ash with fully geopolymerized brick confirms this shift, serving as a qualitative indicator of reaction completion.

VIII. DURABILITY PROPERTIES

A. Resistance to Sulfate Attack

Conventional OPC bricks are vulnerable to sulfate attack, which causes expansive ettringite formation and eventual spalling. Geopolymer bricks, lacking the free calcium aluminate phases that produce ettringite, demonstrate markedly superior sulfate resistance. Studies consistently report mass loss of less than 5% after 28-day immersion in 5% Na_2SO_4 solution, compared to 10–20% for OPC-based bricks. [20,28]

B. Acid Resistance

Strength losses of only approximately 3–5% were recorded for geopolymer bricks after 28-day immersion in 5% H_2SO_4 and 3.5% NaCl solutions, demonstrating excellent chemical resistance in both acidic and saline environments. [18,20]

C. Thermal and Fire Resistance

Geopolymer bricks maintain structural integrity at temperatures that would destroy conventional bricks. The Si–O–Al backbone is inherently stable at elevated temperatures, and geopolymer bricks have demonstrated compressive strength retention of 60–80% after exposure to 600–800°C. [29]
Geopolymers synthesized through alkali activation of aluminosilicate precursors offer compressive strengths up to 100 MPa, thermal stability up to 800°C, and ultra-low permeability levels. [44]

D. Chloride Penetration and Efflorescence

Chloride ion penetration — a key concern for bricks used in coastal or de-iced environments —

is substantially lower in geopolymer systems than in OPC systems. At an optimum fiber dosage, RCPT values dropped from 3100 to 1600 coulombs, shifting chloride penetrability from moderate to low. [27,43] Efflorescence, caused by migration of alkalis to the brick surface, remains a recognized challenge and can be mitigated by reducing the activator dosage or incorporating supplementary calcium-bearing materials.

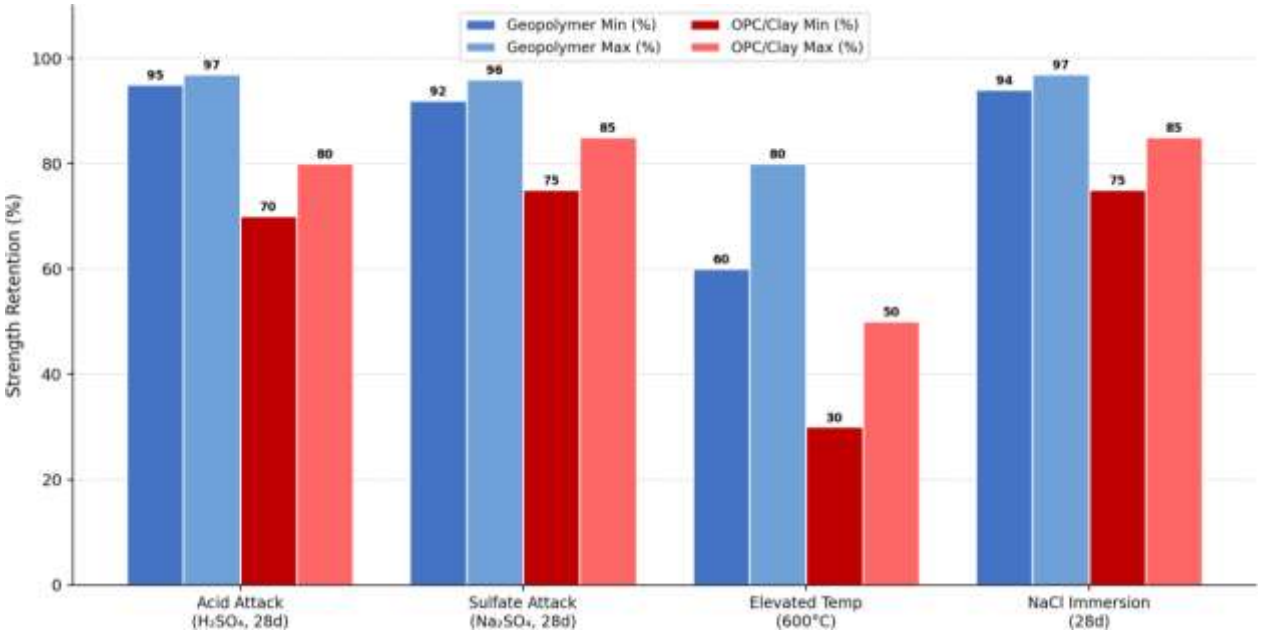

Figure 3: Strength Retention (%) After Durability Tests — Geopolymer vs Conventional Bricks (Sources: [17, 27, 28, 29])

Table III: Strength Retention (%) After Durability Tests — Geopolymer vs Conventional Bricks

Durability Test	Geopolymer Brick (%)	OPC/Clay Brick (%)
Acid Attack (H_2SO_4, 28d)	95-97	70-80
Sulfate Attack (Na_2SO_4, 28d)	92-96	75-85
Elevated Temperature 600°C	60-80	30-50
NaCl Immersion (28d)	94-97	75-85

IX. THERMAL PROPERTIES AND ENERGY EFFICIENCY

A. Thermal Conductivity

Thermal conductivity governs the energy performance of masonry walls. Lower thermal conductivity translates to better insulation and reduced HVAC energy demand. Geopolymer bricks, particularly those incorporating lightweight aggregates, foamed precursors, or air-entraining admixtures, achieve thermal conductivities as low as 0.2–0.5 W/m·K, compared to 0.6–1.0 W/m·K for conventional clay bricks. [17,30] A fly ash-based geopolymer brick incorporating an air-entraining additive

achieved the best balance between structural performance and thermal insulation. [30]

B. Thermal Mass and Passive Design

The relatively high specific heat capacity of geopolymer bricks — comparable to dense concrete — makes them suitable for passive thermal mass applications in climates with significant diurnal temperature variation. Heat absorbed during the day is released slowly at night, moderating indoor temperature fluctuations without mechanical HVAC assistance.

X. ENVIRONMENTAL IMPACT AND LIFE CYCLE ASSESSMENT

A. CO_2 Emissions

The environmental case for geopolymer bricks is compelling. The CO_2 emission of geopolymer concrete can be reduced by 62.73% compared to ordinary Portland cement concrete, with the alkaline solution to fly ash ratio being the most influential factor on CO_2 emissions. [33] A more conservative estimate from Monte Carlo uncertainty analysis places the reduction at approximately 43%, accounting for the significant CO_2 contribution of NaOH and Na_2SiO_3 production. [35] An 80% reduction in CO_2 emissions compared to ordinary Portland cement has also been demonstrated. [36]

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B. Energy Consumption

Geopolymer bricks cured at ambient temperatures require no kiln firing, eliminating the energy-intensive sintering stage that accounts for 60–70% of the energy consumed in fired clay brick production. Even elevated-temperature curing at 60–80°C consumes significantly less energy than kiln firing, particularly when waste heat from industrial processes is utilized.

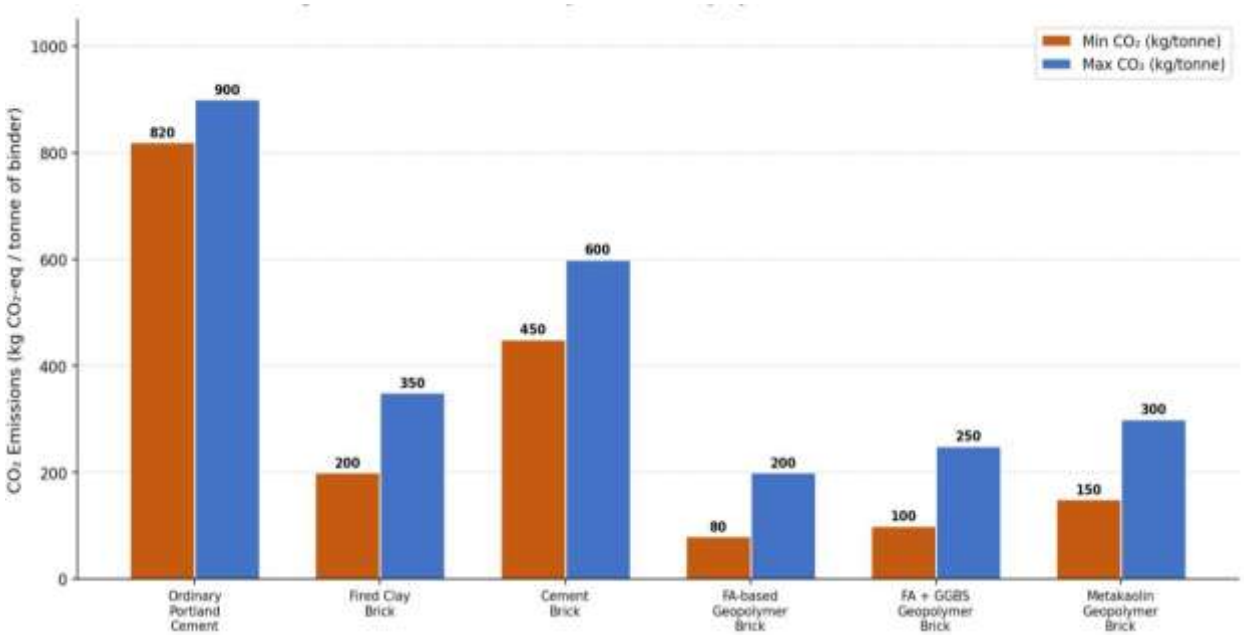

Figure 4: CO_2 Emissions Comparison — Geopolymer vs Conventional Binders (kg CO_2-eq/tons) (Sources: [32, 33, 35])

Table IV: CO_2 Emissions Comparison — Geopolymer vs Conventional Binders

Material	CO_2 Emissions (kg CO_2-eq/tonne)
Ordinary Portland Cement	820-900
Fired Clay Brick	200-350
Cement Brick	450-600
FA-based Geopolymer Brick	80-200
FA + GGBS Geopolymer Brick	100-250
Metakaolin Geopolymer Brick	150-300

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C. Waste Valorization

The use of industrial by-products such as fly ash, GGBS, and CDW in geopolymer brick production diverts millions of tons of waste from landfills annually. Around 120 million tons of fly ash are produced yearly in India through coal combustion, covering nearly 15,000 hectares of useable land — a waste management challenge that geopolymer brick production can directly address. [5]

XI. ECONOMIC FEASIBILITY AND COST ANALYSIS

The cost competitiveness of geopolymer bricks relative to conventional bricks is a function of the local availability and price of precursors, activators, and energy. In regions with abundant fly ash (near thermal power plants), geopolymer bricks can be produced at costs comparable to or lower than cement bricks, particularly when elevated-temperature curing is avoided. Analysis using a linear programming model found that geopolymer brick formulations based on granite waste powder and iron chips had lower embodied energy and carbon emissions than standard industrial cement mixes. [30]

The cost of NaOH and Na_2SiO_3 remains the primary economic barrier to large-scale geopolymer brick production. Strategies to mitigate this include using agricultural silica (rice husk ash) as a partial silicate replacement, optimizing activator quantities through mix design, and utilizing locally produced caustic soda.

IV. RESULTS AND DISCUSSION

A. Precursor Variability: The chemical composition of fly ash varies by source and coal type, requiring mix design recalibration for each source material. This variability complicates standardization and quality control at industrial scale.

B. Handling of Alkaline Activators: NaOH and Na_2SiO_3 are highly corrosive, requiring specialized handling protocols, protective equipment, and storage infrastructure that add to production costs.

C. Lack of Harmonized Standards: While IS 1077, ASTM C62, and EN 771 govern conventional bricks, there are no dedicated international standards for geopolymer bricks,

complicating regulatory acceptance and market adoption.

D. Efflorescence and Shrinkage: The migration of unreacted alkalis to the brick surface causes white surface deposits that affect aesthetics and may indicate incomplete polymerization. Geopolymer systems — particularly those with low calcium content — can also exhibit autogenous shrinkage during drying, which may cause surface cracking if not controlled through mix design or curing optimization.

V. FUTURE SCOPE

A. Machine Learning and Response Surface Methodology: The large number of interacting mix design variables makes empirical optimization laborious. Machine learning models trained on published experimental data can provide accurate strength and durability predictions at a fraction of experimental cost. RSM-based multi-objective optimization can simultaneously maximize strength and minimize CO_2 for specific regional raw material profiles

B. One-Part Geopolymer Bricks: Current two-part geopolymer systems require pre-preparation of corrosive alkaline solutions. Research into one-part geopolymers — where the solid activator is pre-blended with the precursor — would dramatically simplify production, improve safety, and enable decentralized small-scale manufacturing in developing regions.

C. Standardization and Code Development: Collaborative work between research institutions, industry bodies (BIS, ASTM, CEN), and regulatory agencies is urgently needed to develop dedicated test standards and performance specifications for geopolymer masonry units. This is a prerequisite for large-scale commercial adoption.

D. Industrial Symbiosis and Regional Waste Mapping: Systematic mapping of industrial waste streams at the district or regional level would enable targeted geopolymer brick plants to be sited where precursor supply is maximized and transport distances minimized.

E. 3D-Printing of Geopolymer Bricks: Additive manufacturing of geopolymer bricks offers the potential for custom geometries that improve both structural performance and thermal insulation. Early demonstrations of 3D-printed geopolymers show promising results, but printability requires dedicated research.

F. Durability Databases and Field Performance Monitoring: Most published durability data come from accelerated laboratory tests. Long-term field monitoring programs for geopolymer brick structures in different climatic zones are needed to validate laboratory predictions and build confidence among specifiers and regulatory bodies.

G. Reduction of Alkaline Activator Dependency: Exploring alternative activators including solid activators, seawater alkalis, industrial waste liquors, and calcium carbide residue could reduce cost and improve safety. Partial replacement of Na_2SiO_3 with RHA-derived amorphous silica has already shown promise and warrants further systematic investigation. [13,15]

VI. CONCLUSION

This review has synthesized findings from 45 peer-reviewed studies to provide a comprehensive assessment of geopolymer bricks across their synthesis, material characterization, mechanical and durability performance, thermal behavior, and environmental impact. The principal conclusions are as follows:

1. Geopolymer bricks can be synthesized from a wide range of industrial by-products — fly ash, GGBS, metakaolin, CDW, agro-residue ashes, and multi-waste blends — offering significant regional flexibility.

2. Compressive strengths of 8–70 MPa are achievable depending on precursor chemistry, activator type, Si/Al ratio, and curing regime, satisfying classification requirements of IS 1077, ASTM C62, and EN 771 across the spectrum from common to engineering brick.

3. Geopolymer bricks demonstrate superior durability compared to conventional alternatives, with acid and sulfate resistance improvements of 15–25% and thermal stability up to 800°C.

4. Life cycle assessment data consistently support CO_2 emission reductions of 43–80% relative to OPC, representing one of the most significant decarbonization opportunities available to the masonry sector.

5. Key barriers activator cost and corrosivity, precursor variability, absence of dedicated standards, and efflorescence are addressable through targeted research, process engineering, and policy engagement.

6. The future of geopolymer bricks lies at the intersection of materials science, digital manufacturing, industrial ecology, and regulatory harmonization.

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