Collegiate Research Journals

OPEN ACCESS

Archives of Modern Natural Sciences
Vol 5(3) pp. 001-007 May, 2025.
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Full Length Manuscript

Geopolymer Concrete in China: Materials, Performance, Sustainability, Engineering Applications, Standards, and Future Prospects – A Critical Review

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Accepted 12th February 2025

Abstract

China's scale of infrastructure development, large cement and concrete market, and substantial generation of industrial by-products create a distinctive setting for the development of geopolymer concrete (GPC). This review critically examines the state of GPC research and engineering development in China, with emphasis on fly ash, ground-granulated blast-furnace slag, steel slag, metakaolin, and other aluminosilicate precursors; alkaline activation; mixture design; curing; mechanical performance; durability; environmental performance; and implementation. The review synthesizes established international research with China-specific studies and standards. The evidence indicates that fly ash/slag-based GPC can provide high early or ultimate strength, dense microstructures, and useful resistance to chloride ingress, sulfate and acid exposure when precursor chemistry, activator composition, liquid-to-binder ratio, curing, and pore structure are appropriately controlled. At the same time, performance is highly mixture-dependent, and low-calcium fly-ash systems can exhibit carbonation, freeze–thaw, efflorescence, and ambient-curing limitations. China has already established a national standard for alkali-activated slag–fly ash concrete for corrosion-resistant cement products, GB/T 29423-2012, and a revised chemically activated concrete standard, GB/T 29423-2026, has been issued with implementation scheduled for 2027. The review argues that China's greatest opportunity is not simply to substitute cement with a single geopolymer formulation, but to develop regionally adapted, performance-based alkali-activated concrete systems integrated with industrial-residue management, recycled aggregates, digital mix optimization, life-cycle assessment, and standardized durability testing. Key research priorities include precursor variability, activator supply-chain impacts, long-term carbonation and freeze–thaw behavior, reinforcement compatibility, leaching and environmental safety, construction-scale curing, quality assurance, and harmonized performance-based standards.

Keywords: Geopolymer concrete; alkali-activated materials; fly ash; blast-furnace slag; steel slag

1. Introduction

Concrete is the dominant structural material in modern infrastructure, but its conventional Portland-cement binder is associated with substantial energy use and process emissions. The cement sector remains difficult to decarbonize, and the International Energy Agency has highlighted the need for material-efficiency measures, clinker reduction, alternative binders, and other low-emission technologies [11]. China is particularly important in this transition because of the scale of its cement and infrastructure industries and the concentration of industrial mineral residues suitable for alkali activation. The combination of coal combustion residues, metallurgical slags, mineral processing residues, and construction and demolition wastes provides a potentially large feedstock base for alternative binders.

Geopolymer concrete is broadly understood as concrete in which an inorganic aluminosilicate binder is produced by activating reactive silicon- and aluminum-bearing materials with alkaline solutions. The term overlaps with, but is not identical to, the broader category of alkali-activated materials (AAMs). Low-calcium fly ash commonly forms an alkali-aluminosilicate network, whereas calcium-rich slag-containing systems can develop mixtures of calcium-aluminosilicate-hydrate (C-(A)-S-H) and alkali-aluminosilicate-hydrate (N-A-S-H) type gels [1,2]. This distinction is important for China because locally available precursors vary strongly by industrial region and production technology.

Research on geopolymer binders has progressed from laboratory-scale synthesis to concrete mix design, durability assessment, reinforcement interaction, prefabrication, and field-oriented applications. Reviews consistently report promising strength and durability, but also identify unresolved issues involving workability, curing sensitivity, activator handling, precursor variability, cost, standards, and life-cycle impacts [2,3,12]. China-specific studies have additionally examined carbonation, freeze–thaw performance, activator effects, steel-slag and gasification-fly-ash systems, recycled aggregates, and geopolymer applications in transportation infrastructure [5,7,13–16].

The objective of this review is therefore to provide a China-focused synthesis rather than a generic overview. The paper addresses: (i) the material-resource context in China; (ii) geopolymer chemistry and mixture design; (iii) fresh and hardened properties; (iv) durability; (v) environmental and economic considerations; (vi) Chinese standards and implementation; (vii) current and emerging engineering applications; and (viii) research priorities required for reliable large-scale deployment.

2. Review Method and Scope

This manuscript is structured as a critical narrative review. Peer-reviewed review papers, China-based experimental studies, engineering-oriented publications, and publicly available Chinese national-standard records were considered. Priority was given to sources addressing fly ash/slag-based GPC, durability, engineering application, standardization, and China-specific material systems. The literature was interpreted comparatively, recognizing that reported performance depends on precursor composition, activator chemistry, aggregate grading, water content, curing temperature, specimen age, and test protocol. Consequently, isolated numerical values are not treated as universal design limits.

The review uses 'GPC' as an engineering umbrella term while noting that some Chinese standards and publications use 'alkali-activated concrete' or 'chemically activated concrete'. This terminology is retained where necessary to reflect the source or standard accurately [9,10].

3. Why China Is a Strategic Context for Geopolymer Concrete

3.1 Cement decarbonization and material efficiency

Reducing clinker demand is one of the most direct pathways for lowering the embodied emissions of conventional concrete. The IEA reports that global cement-sector emissions remain off track for net-zero alignment and identifies China's clinker-to-cement ratio as an important factor in recent emissions intensity trends [11]. This makes alternative binders relevant to China's broader industrial decarbonization agenda, although the actual benefit of a geopolymer system must be evaluated through life-cycle assessment rather than assumed from the absence of Portland clinker alone.

3.2 Industrial residues as precursor resources

The principal China-relevant precursor families are coal fly ash, blast-furnace slag, steel slag, calcined clay/metakaolin, and selected industrial or municipal mineral residues. Fly ash supplies reactive silica and alumina, while slag contributes calcium and can accelerate setting and strength development. Steel slag and other residues may provide calcium-, iron-, and silicon-bearing phases but require careful characterization because free CaO, MgO, metallic iron, glass content, and mineralogy can affect expansion, durability, and reaction kinetics [2,5].

Table 1. Principal precursor materials relevant to geopolymer concrete development in China

Precursor	Main reactive constituents	Potential role	Key risks/controls
Fly ash	SiO_2, Al_2O_3; variable CaO	Aluminosilicate framework; often used in FA-GPC	Class, fineness, unburnt carbon, glass content, variability
Ground-granulated blast-furnace slag	CaO, SiO_2, Al_2O_3, MgO	Higher early strength; calcium-rich gel formation	Rapid setting, shrinkage, source variability
Steel slag	CaO, Fe oxides, SiO_2, MgO	Secondary reactive/mineral component; filler or binder fraction	Free CaO/MgO, expansion, aging/stabilization
Metakaolin/calcined clay	Reactive SiO_2 and Al_2O_3	Controlled aluminosilicate source; improves reactivity	Calcination energy, cost, particle morphology
Recycled mineral fines	Variable	Circular-economy filler/precursor	Contamination, variable mineralogy, leaching

4. Chemistry and Reaction Mechanisms

The geopolymerization process can be simplified into dissolution of reactive aluminosilicate phases, transport and reorganization of dissolved silicate/aluminate species, polycondensation, and development of a three-dimensional binding network [1,17]. The precise reaction products depend on precursor chemistry. Low-calcium fly ash commonly produces N-A-S-H-type aluminosilicate gel, while calcium-rich slag promotes C-(A)-S-H-type products and mixed gels. The coexistence of these phases can be beneficial because calcium-rich components can improve setting and early strength while aluminosilicate-rich components contribute to network formation and chemical stability [2,18].

Sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium silicate (Na_2SiO_3), and combinations of hydroxides and silicates are frequently used activators. Activator concentration affects dissolution, while silicate modulus and soluble-silica content influence polymerization and gel structure. Excessive alkalinity does not automatically improve performance: it can increase cost, efflorescence risk, heat release, or undesirable residual alkali. Accordingly, activator optimization should be treated as a multi-objective problem involving strength, setting, durability, safety, environmental burden, and cost [2,4,12].

5. Mix Design and Processing

Unlike Portland-cement concrete, GPC mix design cannot be reduced to a single water-to-cement ratio. Important variables include precursor chemistry, binder-to-aggregate ratio, activator-to-binder ratio, Na_2SiO_3/NaOH ratio or silicate modulus, total liquid content, water content, superplasticizer compatibility, curing regime, and aggregate grading [2,4]. For engineering practice, these variables should be optimized against a specified performance envelope rather than selected solely from published recipes.

Table 2. Major geopolymer concrete mixture-design variables and their expected influence

Variable	Typical influence	China-specific practical consideration
Fly ash/slag ratio	Controls setting, early strength, gel chemistry and durability	Use local precursor characterization rather than assuming a fixed ratio
Activator concentration	Controls dissolution and reaction rate	Balance performance with activator cost and handling safety
Silicate modulus	Influences polymerization, viscosity and gel structure	High silicate content can increase cost and workability challenges
Liquid/binder ratio	Controls workability, porosity and strength	Low ratios improve strength but may reduce constructability
Curing temperature/time	Strongly affects low-calcium FA systems	Heat curing is easier in precast production than cast-in-place construction
Slag content	Generally accelerates setting and strength development	Useful for ambient curing but can increase shrinkage/thermal sensitivity
Aggregate grading	Controls packing, workability and paste demand	Local aggregate availability and recycled aggregate quality must be considered
Admixtures	Can improve workability or modify setting	Compatibility with alkaline media must be experimentally verified

A practical China-oriented design workflow is: (1) characterize the precursor chemically and mineralogically; (2) determine reactive fractions; (3) screen activator chemistry; (4) establish paste and mortar performance; (5) optimize aggregate packing and rheology; (6) validate mechanical and durability properties; and (7) perform life-cycle and cost assessments using locally representative supply chains.

6. Fresh and Hardened Properties

6.1 Workability and setting

Fresh GPC can exhibit rapid slump loss or setting, particularly in slag-rich systems or at high activator concentrations. Workability is affected by activator viscosity, precursor surface area, liquid content, temperature, and admixture compatibility. The literature emphasizes that workability is not simply a secondary issue: poor rheology can prevent reliable batching, pumping, compaction, and finishing even when hardened properties are excellent [2,12].

6.2 Compressive and tensile strength

Well-designed GPC can reach structural-strength ranges comparable with conventional concrete, and high-strength formulations can exceed 60–80 MPa under suitable materials and curing conditions [3,4,19]. However, the reported range is broad because geopolymer systems differ substantially. High-calcium slag generally increases early strength and permits more practical ambient curing, while low-calcium fly ash often benefits from elevated-temperature curing [2,6].

6.3 Microstructure

The mechanical response of GPC is closely related to gel chemistry, pore-size distribution, unreacted precursor particles, and the interfacial transition zone. Studies of fly ash geopolymer concrete indicate that geopolymer gel can refine pore structure and improve the matrix–aggregate interface [7]. China-based research also demonstrates that changing slag content and liquid-to-binder parameters can increase matrix density and improve mechanical properties [13].

7. Durability Performance

7.1 Chloride ingress

Dense geopolymer matrices can provide low permeability and useful resistance to chloride penetration, but performance depends strongly on precursor chemistry and curing. Low-calcium fly ash systems can show relatively high chloride permeability when poorly cured, while slag addition and optimized curing generally improve resistance [6,8]. This is particularly relevant to coastal and de-icing environments in China, where reinforced concrete durability is a major infrastructure concern.

7.2 Sulfate and acid exposure

GPC is frequently reported to have good resistance to sulfuric acid, hydrochloric acid and sulfate environments, although performance depends on calcium content and pore structure [6]. The strong chemical resistance of some systems creates opportunities for drainage structures, wastewater-related infrastructure, industrial floors, and selected marine applications.

7.3 Carbonation

Carbonation is more complicated. Some alkali-activated fly ash systems have shown weaker carbonation resistance than ordinary Portland cement concrete, with associated changes in porosity and mechanical properties [8]. A China-based study of fly ash–slag GPC found that both high-temperature curing and slag proportion affected carbonation behavior [5]. Consequently, GPC should not be described categorically as 'more durable' than Portland cement concrete; durability must be exposure-specific and mixture-specific.

7.4 Freeze–thaw and efflorescence

Freeze–thaw resistance can be a limitation for some low-calcium fly ash systems. Chinese review literature reports that slag and metakaolin additions, optimized curing, reduced water content, and other pore-structure controls can improve performance [8]. Efflorescence, caused by migration and reaction of soluble alkalis, remains a practical concern, especially where excess alkali and open pore networks coexist.

Table 3. Durability characteristics of geopolymer concrete and principal control measures

Exposure/property	General response	Main controlling factors	Recommended validation
Chloride penetration	Often low in dense, well-cured systems	Slag content, curing, porosity, liquid/binder ratio	RCPT or migration tests plus long-term diffusion assessment
Sulfate attack	Often favorable	Calcium content, gel chemistry, pore structure	Immersion/expansion and strength-retention tests
Acid attack	Can be favorable	Calcium content and matrix density	Mass/strength loss and surface degradation
Carbonation	Variable; may be weaker in some FA systems	Ca/Si ratio, curing, porosity, alkalinity	Accelerated and natural carbonation with reinforcement monitoring
Freeze–thaw	Highly mixture-dependent	Pore structure, slag/metakaolin, saturation	Repeated freeze–thaw cycles and dynamic modulus
Efflorescence	Potential risk	Free alkali, moisture movement, pore network	Visual rating, soluble alkali and transport testing
High temperature	Often good residual performance	Binder chemistry, moisture, aggregate type	Residual strength and thermal cracking tests

8. Environmental Performance and Life-Cycle Considerations

The environmental case for GPC arises primarily from reducing clinker use and valorizing industrial by-products. Published reviews report potentially substantial reductions in CO_2 emissions relative to Portland-cement concrete, but the magnitude varies widely with precursor source, activator production, curing energy, transport, and allocation rules [3,4,12]. Recent reviews report reductions on the order of 40–80% in favorable

systems, while other studies report smaller reductions once activators and processing are included [3,4]. These ranges should therefore be interpreted as scenario-dependent rather than as an intrinsic property of all GPC.

For China, life-cycle assessment should explicitly include sodium silicate and sodium hydroxide manufacture, electricity mix, transport distance, precursor allocation, precursor drying or grinding, heat curing, and end-of-life scenarios. A geopolymer using a locally available residue with minimal processing may have a substantially different environmental profile from an otherwise identical mixture that relies on long-distance transport and energy-intensive activators.

Table 4. Life-cycle hotspots for China-oriented geopolymer concrete

Life-cycle stage	Potential benefit	Potential burden	Priority action
Precursor supply	Waste/residue valorization	Grinding, drying, transport	Use regional material mapping and allocation sensitivity
Activator production	Enables low-clinker binder	Chemical production can be carbon- and energy-intensive	Lower-carbon silicate/hydroxide supply and optimized dosage
Mixing/curing	Potentially lower binder-related emissions	Heat curing can increase energy demand	Prefer ambient curing where performance permits
Construction	Potentially lower cement demand	Different handling and quality-control requirements	Train contractors and validate pumping/finishing procedures
Service life	Potential durability benefits	Uncertain long-term behavior for some systems	Use exposure-specific durability models
End of life	Potential aggregate/material recovery	Limited field data	Develop circular-design and recycling protocols

9. Chinese Standards, Codes, and Engineering Readiness

Standardization is central to commercialization. China has an established national standard, GB/T 29423-2012, titled 'Alkali-activated slag-fly ash concrete for anticorrosive cement products', which was issued in 2012 and implemented in 2013 [9]. This is significant because it demonstrates that chemically activated slag–fly ash concrete has already entered the national standardization framework, although the scope is specific rather than a universal structural-concrete code.

A new national standard, GB/T 29423-2026, titled 'Chemically activated concrete for corrosion-resistant cement products', was issued on 2 July 2026 and is scheduled to take effect on 1 February 2027, superseding GB/T 29423-2012 [10]. The transition indicates continuing development of China’s standardization framework. Broader implementation, however, still requires performance-based specifications that cover structural design, reinforcement compatibility, durability, quality control, curing, field production, and acceptance testing.

International reviews likewise identify lack of dedicated codes and standardized performance procedures as major barriers to GPC deployment [2,12]. For China, the most useful regulatory direction is therefore likely to be performance-based rather than recipe-based: designers should specify strength, durability, shrinkage, fire performance, permeability, reinforcement protection, and service-life requirements, while allowing validated binder systems to meet those requirements.

Table 5. Standardization pathway for wider GPC adoption in China

Area	Current/near-term need	Suggested performance basis
Materials	Consistent classification of precursor reactivity	Chemical/mineralogical characterization and reactive-content limits
Mix design	Validated proportioning methods	Strength, rheology, setting and durability targets
Structural design	Design rules for reinforced GPC	Bond, cracking, creep, shrinkage and fire performance
Durability	Unified exposure protocols	Chloride, carbonation, sulfate, freeze–thaw and chemical attack
Quality control	Construction-site procedures	Batch-to-batch activator and precursor verification

Environmental safety	Leaching and contaminant assessment	Risk-based limits and end-of-life testing
LCA	Consistent accounting	China-specific datasets and transparent allocation

10. Engineering Applications in China

The most credible near-term applications are those where geopolymer properties align with controlled production environments or demanding exposure conditions. Precast products are particularly attractive because heat curing can be integrated into factory processes and quality control is more consistent than on a construction site. Potential products include sleepers, pipes, panels, precast drainage units, blocks, pavement elements, and corrosion-resistant cement products.

Transportation infrastructure is another promising domain. Recent work on fly ash–steel slag geopolymer concrete sleepers reported compressive strengths up to 72.5 MPa under optimized curing, illustrating the potential for rail applications while also showing the importance of mixture-specific validation [16]. Research using excavated rock and soil, fly ash and slag has also demonstrated the potential to combine geopolymer binders with reclaimed aggregate resources, with reported reductions in cost and greenhouse-gas emissions relative to the study's conventional reference concrete [15].

For cast-in-place structural concrete, the barriers are greater because ambient curing, workability retention, reinforcement protection, construction scheduling, and contractor familiarity become decisive. Consequently, China's deployment strategy can reasonably prioritize standardized precast products and infrastructure components while the evidence base for general structural applications continues to develop.

Table 6. Potential application classes and deployment requirements

Application	Technical opportunity	Main deployment issue	Readiness priority
Precast pipes and drainage	Controlled curing; corrosion resistance	Standards and long-term field validation	High
Railway sleepers	High strength and industrial production	Fatigue, dynamic loading and durability	High
Pavement/blocks	High early strength; residue utilization	Surface durability and quality control	High
Marine/coastal components	Potential chloride/sulfate resistance	Carbonation and reinforcement durability	Medium
Structural frames	Clinker reduction and high strength	Design codes, bond, creep/shrinkage, field curing	Medium
3D-printed concrete	Tailored rheology and low-clinker binders	Printability, interlayer bond and standards	Emerging

11. Economic and Supply-Chain Considerations

The economic performance of GPC depends on the local balance between precursor value, activator price, processing, transport, curing, and avoided cement use. The assumption that GPC is automatically cheaper than conventional concrete is not justified. Activators can be a significant cost component, while residue availability can reduce binder costs in regions close to major industrial sources [12].

China’s large industrial base creates an opportunity for regional supply chains: blast-furnace slag and steel slag near major steel-producing clusters, fly ash near coal-intensive regions, and calcined clays where suitable mineral resources and processing capacity exist. However, the decline or relocation of coal-fired generation and changes in industrial production can alter the future availability of traditional precursors. A resilient GPC industry should therefore avoid dependence on a single waste stream and develop multi-precursor formulations.

12. Key Challenges and Research Gaps

Despite substantial progress, five categories of uncertainty remain important for China: material variability, long-term durability, construction practice, environmental assessment, and standardization.

Table 7. Major research gaps and recommended research directions

Research gap	Why it matters in China	Recommended direction
Precursor variability	Industrial residues differ by region and process	Build regional databases linking chemistry, mineralogy and performance
Activator sustainability	Activator manufacture can offset binder benefits	Develop lower-carbon solid, hybrid and alternative activators
Ambient curing	Essential for cast-in-place construction	Optimize slag/metakaolin/hybrid systems for reliable ambient curing
Carbonation	Affects reinforcement protection and service life	Long-term natural exposure plus coupled transport/mechanical models
Freeze–thaw	Important in northern climates	Standardized cyclic tests and pore-structure design
Reinforced GPC	Structural use requires reliable bond and cracking data	Bond, corrosion, creep, shrinkage and structural-scale testing
Leaching	Residue-based binders may contain trace contaminants	Risk-based leaching protocols and field monitoring
LCA/LCC	Results are supply-chain dependent	China-specific databases, uncertainty analysis and transparent allocation
Construction QA	Field variability can exceed laboratory variability	Digital batching, real-time rheology and acceptance criteria
Standards	Code uncertainty limits adoption	Performance-based national and sector-specific standards

13. Future Development Pathways

Future GPC development in China is likely to move from single-waste-stream systems toward engineered multi-precursor binders. Hybrid fly ash–slag systems are particularly attractive because they can combine the aluminosilicate reactivity of fly ash with the calcium-assisted strength development of slag. Steel slag, calcined clay, recycled glass, tunnel-excavation materials, and other mineral residues can further expand the feedstock base when their chemistry and durability are controlled [15,16].

Digital materials engineering offers another pathway. Machine learning and response-surface methods can link precursor chemistry and mixture variables to strength, workability, and durability, reducing trial-and-error optimization. However, predictive models must be trained on geographically diverse datasets because a model developed from one fly ash or slag source may not generalize to another.

Carbon-aware construction should also move beyond binder substitution. A complete system includes optimized structural design, lower cementitious intensity, recycled aggregates, longer service life, repairability, and end-of-life recovery. The relevant comparison is therefore not 'GPC versus OPC' in isolation but the life-cycle performance of competing structural systems.

14. Conclusions

- China provides a particularly important context for geopolymer concrete because of the scale of its concrete industry and the availability of diverse industrial mineral residues suitable for alkali activation.
- Fly ash and blast-furnace slag remain important precursor families, while steel slag, calcined clays, recycled mineral fines and other residues can broaden the resource base.
- GPC can achieve structural and high-strength performance, but results are strongly dependent on precursor chemistry, activator formulation, liquid content, curing, aggregate packing and testing methodology.

- Durability is exposure-specific. Chloride, sulfate and acid resistance can be favorable, whereas carbonation, freeze–thaw and efflorescence require targeted mixture design and validation.
- Environmental benefits should be established using life-cycle assessment that includes activator manufacture, precursor processing, transport and curing energy; clinker elimination alone does not guarantee a lower-impact concrete.
- China has an established national standard for alkali-activated slag–fly ash concrete and has issued a 2026 revision with implementation scheduled for 2027, indicating continuing progress in standardization.
- Near-term commercialization is especially suitable for precast and infrastructure products where curing and quality control can be tightly managed. Broader cast-in-place structural use requires stronger evidence on reinforcement behavior, long-term durability and construction-site quality assurance.
- The most important research priorities are regional precursor databases, low-carbon activators, ambient-cure formulations, long-term durability, structural-scale validation, leaching assessment, China-specific LCA/LCC datasets, and performance-based standards.

15. Declarations

Funding: No external funding is declared for this review manuscript.

Conflict of interest: The author declares no known competing financial or personal interests that could have influenced the work.

Data availability: No new experimental dataset was generated. The manuscript synthesizes published literature and publicly available standards information.

Author contribution: Conceptualization, literature synthesis, analysis, writing, and revision: Author.

Ethics approval: Not applicable.

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