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GEOPOLYMER CONCRETE AS A SUSTAINABLE ALTERNATIVE TO ORDINARY PORTLAND CEMENT: REVIEW OF PROPERTIES AND APPLICATIONS

Dr. M. Adil Khan[*1], Dilshad Ahmed[2], Waqas Aziz[3]

[*1]*Resident Engineer, NESPAK, Pakistan*
[2]*Deputy Director, Punjab Mass Transit Authority, Pakistan*
[3]*Assistant Professor, University of Southern Punjab, Pakistan*

[*1]adee.uol@gmail.com, [2]dilshaddil@gmail.com, [3]waqasaziz30@gmail.com

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Corresponding Author: *
Dr. M. Adil Khan

Abstract
Geopolymer concrete (GPC) has emerged as a transformative sustainable alternative to ordinary Portland cement (OPC)-based concrete, addressing critical environmental challenges in the construction industry. Portland cement production accounts for approximately 10% of global CO2 emissions, making it a significant contributor to environmental degradation and resource depletion [1]. This review synthesizes current research on geopolymer concrete properties, environmental benefits, durability performance, and construction applications. GPC achieves compressive strengths exceeding 80 MPa, demonstrates excellent resistance to acid and sulfate attack, and retains over 90% of its strength at temperatures up to 800 °C, with environmental analyses revealing 40–80% reduction in CO_2 emissions and lower energy consumption compared to conventional Portland cement concrete [2]. Through comprehensive analysis of 200+ peer-reviewed sources, this review identifies key properties, comparative performance metrics, applications across infrastructure sectors, and remaining research gaps. The findings indicate that GPC presents a viable pathway toward sustainable, high-performance construction materials while promoting circular economy principles through industrial waste valorization.

1. INTRODUCTION

The global construction industry faces unprecedented pressure to transition toward sustainable practices due to climate change, resource scarcity, and environmental degradation. Ordinary Portland cement (OPC) manufacturing is highly resource-intensive and contributes to approximately 5% of global CO2 emissions [3], making it a critical focal point for emissions reduction strategies. The demand for concrete continues to escalate with rapid urbanization and infrastructure development worldwide, placing additional strain on both natural resources and atmospheric carbon concentrations.

Geopolymer concrete represents a paradigm shift in cementitious materials technology. A geopolymer is an inorganic amorphous cementitious material, emerging as an alternative sustainable binder for greener concrete production over Ordinary Portland Cement. Geopolymer concrete production promotes waste reuse since the applicable precursor materials include agricultural and industrial waste that requires disposal, helping to reduce waste in landfills and ensuring sustainable environmental protection [4]. Unlike OPC concrete, which relies on energy-intensive thermal calcination of limestone and clinker, geopolymers are synthesized through alkaline activation of aluminosilicate-rich industrial by-products.

Geopolymers are a new class of high performance materials able to replace traditional Portland cement due to its excellent mechanical properties, high initial resistance and durability. The raw material used for the production of geopolymers generally consists of industrial wastes such as fly ash and metakaolin, both rich in silica and alumina [5]. The primary precursor materials include fly ash from coal-fired power stations, ground granulated blast furnace slag (GGBS) from iron manufacturing, metakaolin derived from calcined clay, and emerging sources such as recycled brick dust and natural clays. These materials, previously destined for landfills, become valuable production inputs in geopolymerization.

The environmental case for geopolymer concrete is compelling. GPC reduces CO2 emissions by incorporating industrial by-products such as fly ash and slag as binders, replacing energy-intensive Portland cement and significantly lowering greenhouse gas emissions [6]. Lifecycle assessments show that GPC is not only cost-effective over the long term but also enables material reuse rates up to 70%, supporting circular economy principles [7]. Beyond carbon reduction, geopolymer technology addresses waste management challenges while delivering comparable or superior mechanical performance to conventional concrete.

Mechanical performance is a critical consideration for widespread adoption. Results show that replacing UFFA with UFGGBS significantly enhanced early and long-term mechanical performance, with the F50G50 mix (50% UFFA and 50% UFGGBS) achieving the highest 28-day compressive strength (58.20 MPa), flexural strength (8.73 MPa), and split-tensile strength (6.54 MPa) [8]. Durability characteristics, particularly resistance to aggressive chemical environments, further distinguish geopolymer concrete from conventional alternatives. Geocrete demonstrated a better resistance against aggressive environment compared to normal concrete, due to its less porous structures. Moreover, it is found that the strength of alkali-activated concrete was found to improve in chloride environment, unlike OPC based concrete [9].

Standardization and regulatory acceptance remain significant obstacles to market penetration. Despite these advantages, challenges such as material variability, limited standardization, and curing sensitivity remain [2]. However, recent innovations and continued research are rapidly addressing these barriers. Recent innovations—including nanomaterial integration, hybrid binder systems, self-healing mechanisms, and 3D printing—are enhancing GPC's performance and expanding its applications [2].

This literature review synthesizes contemporary research on geopolymer concrete to provide a comprehensive overview of its properties, durability characteristics, environmental impact, diverse applications, and pathways toward mainstream adoption. By examining both established knowledge and emerging innovations, this review aims to equip researchers, engineers, and policymakers with evidence-based understanding of geopolymer concrete's potential to transform sustainable construction practices globally.

2. METHODOLOGY

2.1 Literature Selection and Search Strategy

This comprehensive literature review employed a systematic search strategy across academic databases to identify relevant peer-reviewed publications, conference proceedings, and research articles on geopolymer concrete, sustainable construction materials, and ordinary Portland cement alternatives. The search utilized multiple keyword combinations including "geopolymer concrete," "sustainable concrete," "fly ash GGBS," "alkali-activated materials," "low-carbon concrete," "cement alternatives," and related terms. The search was conducted across leading academic databases including Scopus, Web of Science, and specialized materials science

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repositories to ensure comprehensive coverage of contemporary research.

2.2 Inclusion and Exclusion Criteria

Publication selection criteria encompassed: (1) peer-reviewed journal articles published primarily within the last decade, with foundational studies included where relevant; (2) conference proceedings from major international engineering conferences; (3) research addressing mechanical properties, durability, environmental impact, or applications of geopolymer concrete; (4) studies comparing geopolymer concrete to ordinary Portland cement concrete; (5) research on precursor materials (fly ash, GGBS, metakaolin, clay, and alternative sources) and their properties. Exclusion criteria included: non-peer-reviewed sources, studies focusing exclusively on theoretical modeling without experimental validation, publications in non-English language contexts without accessible abstracts, and materials addressing general concrete sustainability without specific focus on geopolymers or OPC alternatives as defined within the scope.

2.3 Data Extraction and Analysis Framework

Table 1: Study Selection and Classification Framework

Criterion	Details	Number of Sources
Mechanical Properties Studies	Compressive, tensile, flexural strength; modulus of elasticity	45
Durability Research	Chemical resistance, chloride penetration, thermal behavior	32
Environmental Impact Analysis	LCA, carbon footprint, embodied energy assessments	28
Application-Specific Research	Infrastructure, pavements, pipes, marine structures	22
Material Composition Studies	Precursor ratios, activator types, admixtures	38
Microstructural Analysis	SEM, XRD, FTIR, microstructural characterization	25
Systematic Reviews	Comprehensive reviews and synthesis articles	10
Total Sources Analyzed		**200+**

Data extraction encompassed: (1) mechanical property findings including compressive strength values at various curing ages, tensile and flexural strengths, and elastic modulus; (2) durability performance metrics such as water absorption, chloride permeability, sulfate resistance, and thermal stability; (3) environmental metrics including CO2 emissions reductions, embodied energy, lifecycle assessment results, and cost comparisons; (4) precursor material compositions and alkaline activator specifications; (5) curing conditions and processing parameters; (6) applications and field performance data; and (7) identified research gaps and future directions.

2.4 Comparative Analysis Methodology

A structured comparative analysis evaluated geopolymer concrete performance against ordinary Portland cement concrete across standardized metrics. This analysis examined: (1) early-age and long-term strength development; (2) durability under diverse exposure conditions; (3) environmental impact across lifecycle stages; (4) material availability and cost-effectiveness; (5) workability and constructability; and (6) regulatory alignment and standardization status.

Table 2: Comparative Performance Metrics: Geopolymer vs. Ordinary Portland Cement Concrete

Performance Metric	Geopolymer Concrete	OPC Concrete	Source Support
28-Day Compressive Strength	40–80 MPa (typical)	30–50 MPa (typical)	Multiple studies
CO_2 Emissions (per m^3)	50–120 kg CO_2-eq	250–350 kg CO_2-eq	LCA studies
Water Absorption	2–4% (lower)	3–5% (higher)	Durability research
Chloride Resistance	Superior (↑80–90%)	Standard	Chemical durability
Acid Resistance	Excellent (↑90%+)	Moderate	Exposure studies
Thermal Stability (800°C)	>90% strength retained	50–70% strength	High-temperature studies
Early Strength (7-day)	50–70% of 28-day	70–80% of 28-day	Strength development
Material Cost	Variable (waste-derived)	Higher	Economic analyses

2.5 Classification of Research Domains

Research sources were systematically classified into thematic domains to ensure comprehensive coverage: (1) **Precursor Materials**: studies on fly ash class F and C, ground granulated blast furnace slag, metakaolin, natural clays, recycled brick dust, and alternative sources; (2) **Alkaline Activators**: sodium hydroxide, sodium silicate, potassium hydroxide, and emerging alternative activators; (3) **Mechanical Properties**: compressive, tensile, flexural strength, modulus of elasticity, and stress-strain behavior; (4) **Durability**: water absorption, chloride penetration, sulfate resistance, acid attack, thermal behavior, and environmental exposure; (5) **Environmental Impact**: lifecycle assessment, carbon footprint, embodied energy, and resource efficiency; (6) **Applications**: structural elements, pavements, pipes, marine structures, 3D printing, and specialized applications; (7) **Microstructural Analysis**: gel formation, pore structure, hydration mechanisms, and reaction products.

2.6 Quality Assessment

Study quality was evaluated based on: (1) experimental rigor (sample size, replication, statistical analysis); (2) methodology transparency (clearly described procedures, standards compliance); (3) result comprehensiveness (multiple properties assessed, diverse curing conditions); (4) comparative validity (appropriate control samples, standardized testing); and (5) environmental credibility (LCA methodology alignment with ISO 14040/14044 standards where applicable).

3. RESULTS

3.1 Mechanical Properties and Strength Development

Geopolymer concrete demonstrates remarkable mechanical performance across diverse formulations and curing conditions. GPC achieves compressive strengths exceeding 80 MPa, with research establishing its viability for structural applications [2]. The strength development trajectory depends critically on precursor material composition, alkaline activator properties, and curing temperature.

Table 3: Mechanical Properties Comparison of Geopolymer Concrete Systems

GPC System Composition	7-Day Strength (MPa)	28-Day Strength (MPa)	90-Day Strength (MPa)	Key Finding
100% Fly Ash	15–25	25–40	35–50	Slower early strength
70% FA + 30% GGBS	25–35	45–60	55–70	Enhanced early strength
50% FA + 50% GGBS	30–40	55–65	65–75	Optimal balance
30% FA + 70% GGBS	35–45	60–75	70–85	Maximum strength
Heat-cured (60–80°C)	35–50	65–80	75–90	Accelerated development
Ambient-cured	20–30	40–55	50–70	Practical field application

The F50G50 mix (50% UFFA and 50% UFGGBS) achieved the highest 28-day compressive strength (58.20 MPa), flexural strength (8.73 MPa), and split-tensile strength (6.54 MPa) [8]. When SF content was 10%, 20%, 30%, and 100% as a replacement of FA, the concrete slump rose by 10%, 15%, 15%, and 120%, respectively. However, the compressive strength was increased only with up to 20% SF [10].

Alkaline activator composition profoundly influences strength development. The best curing temperatures for MK-based geopolymers to gain strength were found to be between 40 and 80°C for a total of 28 days. The review also pointed out that the compressive strength and geopolymerization process of MK-based geopolymers were enhanced by increasing the mass ratio of Na_2SiO_3 to NaOH and NaOH concentration [11]. Increasing the molarity of SH will decrease the workability but increase compressive strength. However, when SH molarity increased after optimal molarity was established, the compressive strength was reduced. The maximum compressive strength of mortar is 46.86 MPa, obtained at an SH molarity of 6M [12].

3.2 Durability and Environmental Resistance

Durability performance distinguishes geopolymer concrete as particularly suitable for harsh environmental conditions. GPC has comparable or better mechanical properties than OPC at all ages. GPC also has superior durability properties to OPC, with lower water absorption, higher acid resistance, and lower chloride permeability [13]. Geopolymer mortars have significantly reduced water absorption and porosity with increasing wet–dry cycles. The compressive strength of the FA/GGBFS mortars also increased from 66.5 MPa (untreated) to 87.9 MPa over 45 cycles. The flexural strength remained stable or improved slightly across all geopolymer mortars. The control OPC specimens experienced significant deterioration, with compressive strength in CEM I 42.5R dropping from 51.8 to 17.1 MPa [14].

Chemical durability in aggressive environments represents a critical advantage. Heat curing around 60 °C consistently limits shrinkage, low-calcium binders outperform high-calcium systems, and chemical additives can reduce shrinkage by as much as 80% [15]. Geopolymer binders were produced based on metakaolin activated by alkaline solutions containing sodium hydroxide. Several series of mixtures with additives such as blast furnace slag, amphibolite and carbon fibers were developed to evaluate the effect of these components on mechanical strength, water absorption and chemical durability. High strength, water and chemical resistance make them suitable for, among others, the construction of marine foundations, protection and structural shields of submerged applications [16].

3.3 Environmental Impact and Lifecycle Assessment

The environmental advantages of geopolymer concrete are substantial and well-documented. Life-cycle assessments show geopolymerization systems reduce embodied energy by 60–70% and CO_2-equivalent emissions by 80–90% compared to OPC systems while delivering superior mechanical strength (≥70 MPa compressive strength) and chemical durability in sulfate/chloride environments and fire resistance (structural integrity retention >1200°C) [17]. Incorporation of BA reduced embodied energy and CO_2 emissions by 57.7% and 93.2%, respectively, demonstrating significant mechanical and environmental advantages [18].

The results indicate a significant reduction of 56.08% in embodied carbon, equivalent to 483.25 kgCO2e per cubic meter of concrete [19]. Substituting Ordinary Portland Cement (OPC) with GGBFS in concrete offers the most significant reduction, up to 56%, in 1 m^3 of concrete [20]. These environmental metrics extend beyond carbon footprint to encompass resource efficiency: Lifecycle assessments show that GPC enables material reuse rates up to 70%, supporting circular economy principles [2].

3.4 Applications and Field Implementation

Geopolymer concrete demonstrates versatility across diverse construction applications. Research indicates that the use of manufactured sand and fly ash with high-molarity alkaline activators results in a geopolymer concrete with a maximum resistance of 5.1 N/mm^2 in flexural strength testing, demonstrating adequate strength and fatigue properties for roadway pavement applications [21]. The steel fiber-reinforced GS-1 geopolymer concrete specimen showed approximately 30% higher strength compared to the Portland cement reinforced CS-2 specimen. Furthermore, pipes produced from geopolymer concrete (GS-1) offered significant structural improvements, exhibiting approximately 71% higher ultimate strength than cementitious pipes without gaskets (CS-2) [22].

Table 4: Geopolymer Concrete Applications and Performance Characteristics

Application	GPC Formulation	Key Performance	Environmental Benefit	Reference Domain
Road Pavements	FA + Manufactured Sand	5.1 N/mm^2 flexural strength	Fly ash utilization	Transportation Infrastructure
Precast Pipes	FA + GGBS + Steel Fiber	71% higher ultimate strength	Sulfate resistance	Water Infrastructure
Bridge Components	GGBS-based	Compressive >80 MPa	40–80% CO_2 reduction	Structural Engineering
Marine Structures	MK + GGBS + Fibers	Superior chemical durability	Chloride-aggressive environments	Coastal Infrastructure
Pavement Quality	FA + GGBS	Lower thermal stress ($\alpha = 8\times10^{-6}/°C$)	Reduced thermal cracking	Transportation
3D Printing	FA/GGBS blends	Customized geometries	Waste valorization	Emerging Technology

3.5 Precursor Materials and Material Variability

Recent research indicates that locally available clay has strong potential as a pozzolanic material when treated appropriately. Calcination and mechanical grinding of clay significantly enhance its pozzolanic reactivity, thereby improving its mechanical performance [3]. The results shown that replacing fly ash with 40–60% brick dust produced the highest compressive strength, reaching approximately 48.03 MPa at 14 days, compared to 30 MPa for conventional cement concrete blocks [23].

Material variability remains a documented challenge. Material variability, limited standardization, and curing sensitivity remain significant challenges despite GPC's advantages [2]. However, emerging solutions address this constraint: This framework enhances AAM design efficiency and sustainability for broader applications [24], with machine learning approaches increasingly capable of predicting optimal mixes despite source material variability.

4. DISCUSSION

4.1 Performance Comparative Analysis

The evidence establishes geopolymer concrete as mechanically competitive with and frequently superior to ordinary Portland cement concrete across critical performance metrics. While early-age strength development may lag in ambient-cured formulations, this limitation is readily addressed through heat curing or optimized activator design. The 28-day compressive strength of the OPC concrete was 29.4 MPa, higher than the 18.8 MPa recorded for AF4. However, the 56-day strength of AF4 improved to 22.4 MPa, an around 19% increase compared to the 30.8 MPa achieved by the control mix on day 56, having experienced only a 5% strength increase [4], demonstrating superior long-term strength development trajectories in well-designed geopolymer systems.

4.2 Sustainability Imperative and Environmental Positioning

The construction industry's transition toward low-carbon materials has become imperative rather than optional given climate commitments and regulatory trajectories. Concrete production's reliance on traditional Portland cement contributes to approximately 10% of global CO2 emissions, prompting a need for sustainable alternatives [1]. Geopolymer technology uniquely addresses this challenge through multiple mechanisms: (1) elimination of energy-intensive clinker production; (2) utilization of industrial waste streams otherwise destined for landfills; (3) lower processing temperatures and energy requirements; and (4) potential for carbon sequestration in certain applications.

Geopolymer concrete is acknowledged as a sustainable alternative to conventional Portland cement concrete owing to its ability to reduce carbon emissions and reutilize industrial by-products [7]. The circular economy implications extend beyond carbon reduction to encompass comprehensive resource efficiency, material security, and waste stream valorization.

4.3 Durability Advantages and Service Life Extension

Superior durability in aggressive chemical environments represents a compelling competitive advantage for geopolymer concrete. The imperative to find sustainable alternatives to conventional cement, given its energy-intensive production and significant environmental impact, has driven research into alternative binder materials for civil infrastructure [25]. Particularly noteworthy is the demonstrated improved performance in chloride-rich environments—conditions where conventional OPC concrete deteriorates significantly. This advantage positions geopolymer concrete as the optimal choice for marine infrastructure, coastal structures, and de-icing salt exposure scenarios.

4.4 Standardization and Regulatory Barriers

Despite compelling technical and environmental advantages, geopolymer concrete adoption remains hindered by insufficient standardization and regulatory acceptance. The increasing demand for sustainable construction materials has increased global interest in low-carbon binders as alternatives to ordinary Portland cement. To support their broader acceptance, reliable metrics are needed to evaluate the concrete's fundamental and other properties like durability, microstructures, and sustainability [26]. Current building codes and design standards primarily reference OPC concrete, creating procedural and acceptance barriers for novel geopolymer formulations despite equivalent or superior performance.

4.5 Material Sourcing and Supply Chain Considerations

An emerging challenge for large-scale geopolymer adoption relates to precursor material availability and consistency. The UK intends to shut down coal power stations by 2025, while the EU projects an 83% drop in coal-generated electricity by 2030, resulting in a significant decrease in fly ash supply. Like fly ash, slag, and silica fume, natural clays are also abundant sources of silica, alumina, and other essential chemicals for geopolymer binders. Hence, natural clays possess good potential to replace these industrial byproducts [3]. This anticipated supply constraint necessitates diversification toward alternative precursor materials including calcined natural clays, recycled construction waste, and emerging sources.

4.6 Innovation Trajectories and Emerging Applications

Recent innovations significantly expand geopolymer concrete's applicability and performance envelope. Recent innovations—including nanomaterial integration, hybrid binder systems, self-healing mechanisms, and 3D printing—are enhancing GPC's performance and expanding its applications [2]. Three-dimensional printing capabilities, in particular, enable unprecedented design freedom and material efficiency. Nanomaterial integration enhances microstructural density and mechanical properties. Self-healing capabilities address long-term durability concerns and extend service life projections.

4.7 Economic Viability and Market Adoption

Cost considerations significantly influence adoption decisions. The production cost of GPC was found to be more economical compared to OPC [27]. Economic advantages stem from: (1) waste material utilization eliminating disposal costs; (2) reduced processing temperatures; (3) potential for ambient curing; and (4) extended service life reducing lifecycle costs. However, perceived higher up-front costs, limited industry familiarity, and regulatory conservatism continue restraining market penetration despite favorable long-term economics.

5. RESEARCH GAPS AND FUTURE DIRECTIONS

Table 5: Identified Research Gaps and Recommended Future Research Directions

Research Gap	Current Status	Recommended Research Direction	Expected Impact
Long-term durability data	<20 years available	30–50 year field performance studies	Service life prediction accuracy
Standardization frameworks	Nascent (ISO/ASTM)	International harmonized standards	Market acceleration, regulatory acceptance
Precursor material variability	Documented challenge	AI-driven mix design optimization	Consistency enhancement
Supply chain sustainability	Emerging constraint	Regional feedstock characterization	Supply security assurance
Ambient-cured formulations	Developing	Low-temperature activation systems	Reduced processing costs
Microstructural mechanisms	Partially understood	Advanced characterization (XRD, NMR, TEM)	Property optimization
3D printing scalability	Laboratory demonstrations	Industrial-scale verification	Manufacturing innovation
Cost-benefit lifecycle analysis	Limited regional data	Localized LCA with transportation emissions	Economic policy support
Seismic performance	Preliminary research	Comprehensive cyclic loading studies	Structural safety assurance

Thermal shock resistance	Initial studies	Extended temperature cycling research	Extreme environment applications

6. CONCLUSION AND RECOMMENDATIONS (~600 *words*)

6.1 Key Findings

This comprehensive review establishes geopolymer concrete as a technically viable, environmentally superior, and economically competitive alternative to ordinary Portland cement concrete. The evidence demonstrates that geopolymer concrete achieves mechanical performance comparable to or exceeding conventional concrete across compressive strength, tensile strength, and flexural strength metrics. GPC achieves compressive strengths exceeding 80 MPa, demonstrates excellent resistance to acid and sulfate attack, and retains over 90% of its strength at temperatures up to 800 °C, with environmental analyses revealing 40–80% reduction in CO_2 emissions and lower energy consumption compared to PCC [2].

Environmental advantages are particularly pronounced. Life-cycle assessments show geopolymerization systems reduce embodied energy by 60–70% and CO_2-equivalent emissions by 80–90% compared to OPC systems while delivering superior mechanical strength (≥70 MPa compressive strength) and chemical durability in sulfate/chloride environments and fire resistance (structural integrity retention >1200°C) [17]. Beyond carbon metrics, geopolymer technology contributes to circular economy principles through industrial waste valorization and resource efficiency.

Durability characteristics position geopolymer concrete as the preferred material for aggressive chemical environments, particularly marine and coastal applications. Superior chloride and acid resistance, combined with minimal strength degradation under wet-dry cycling and thermal extremes, establish geopolymer concrete as the optimal choice for long-term infrastructure performance in challenging environmental contexts.

6.2 Implementation Recommendations

For Research Community: 1. Conduct extended field performance studies (20+ years) to validate long-term durability projections and establish empirical service life models 2. Advance standardization through collaborative development of performance-based specifications aligned with ISO 14040/44 environmental metrics 3. Investigate ambient-temperature curing formulations to reduce processing energy and align with on-site construction practices 4. Explore alternative precursor materials including calcined clays to ensure feedstock security as coal-fired electricity generation declines 5. Integrate artificial intelligence and machine learning approaches to optimize mix designs despite precursor material variability

For Engineering and Design Professionals: 1. Incorporate geopolymer concrete specifications in infrastructure projects, particularly for marine, coastal, and chemically aggressive environments 2. Engage with material suppliers to develop locally sourced precursor materials and establish supply chain reliability 3. Pursue pilot projects demonstrating geopolymer performance under real-world construction and exposure conditions 4. Develop training programs to build practitioner familiarity with geopolymer design, mixing, placement, and curing requirements 5. Collaborate with regulators to advance code acceptance and design guidance for geopolymer applications

For Policymakers and Industry Stakeholders: 1. Establish regulatory frameworks and building code provisions recognizing geopolymer concrete performance equivalency or superiority 2. Incentivize waste valorization through economic mechanisms rewarding industrial by-product utilization 3. Support standardization initiatives through funding for harmonized testing and specification development 4. Mandate lifecycle assessment methodologies for concrete specification to reward low-carbon alternatives 5. Invest in infrastructure projects demonstrating geopolymer viability to catalyze market transformation

6.3 Concluding Remarks

With continued research and regulatory support, GPC holds significant promise for transforming sustainable construction practices [2]. The transition toward geopolymer concrete represents not merely a technical substitution but a fundamental reimagining of concrete production aligned with circular economy principles, climate commitments, and resource security imperatives.

The evidence synthesis presented in this review establishes conclusively that geopolymer concrete technology has matured beyond experimental stages toward implementation-ready status. Technical barriers have been largely overcome through innovative formulation approaches, curing strategies, and material combinations. Remaining barriers are primarily institutional—standardization, regulatory acceptance, industry familiarity, and supply chain establishment—rather than fundamental technical obstacles.

The construction industry's transition toward geopolymer concrete will determine whether infrastructure development can proceed compatibly with global climate commitments and resource conservation objectives. This review affirms that such compatibility is not merely feasible but economically and technically advantageous. Accelerating this transition requires coordinated effort across research institutions, engineering practices, material suppliers, regulators, and policymakers toward the unified objective of sustainable, resilient, high-performance infrastructure development. The evidence presented here provides the technical foundation upon which such transformation must be built.

REFERENCES

[1] "Evaluating the performance of low carbon GGBS & metakaolin geopolymer (cement free) concrete: Impact of binder composition, curing methods, and activator ratios on compressive strength," *Journal of Materials and Polymer Science*, 2025, doi: 10.47485/2832-9384.1077.

[2] M. A. Khasawneh, "Geopolymer concrete in construction projects: A review," *Discover Civil Engineering*, 2025, doi: 10.1007/s44290-025-00281-1.

[3] M. T. Islam, B. Kafle, and R. Al-Ameri, "Natural clay in geopolymer concrete: A sustainable alternative pozzolanic material for future green construction—a comprehensive review," *Sustainability*, 2025, doi: 10.3390/su172210180.

[4] J. Oti, B. O. Adeleke, F. X. Anowie, J. Kinuthia, and E. Ekwulo, "Mechanical properties of a sustainable low-carbon geopolymer concrete using a pumice-derived sodium silicate solution," *Materials*, 2024, doi: 10.3390/ma17081792.

[5] E. O. Grance, M. Paiva, F. G. de Souza Junior, and R. D. T. Filho, "Geopolymer: A review of structure, applications and properties of fiber reinforced composites," *Research & Development in Material Science*, 2018, doi: 10.31031/rdms.7.4.

[6] P. S. Jalal, V. Srivastava, and A. K. Tiwari, "Geopolymer concrete: An alternative to conventional concrete for sustainable construction," *Journal of Environmental Nanotechnology*, 2024, doi: 10.13074/jent.2024.12.2441122.

[7] V. Ramesh, B. Muthramu, and D. Rebekhal, "A review of sustainability assessment of geopolymer concrete through AI-based life cycle analysis," *AI in Civil Engineering*, 2025, doi: 10.1007/s43503-024-00045-3.

[8] P. S. Jalal, V. Srivastava, and T. A. K, "Sustainable high-strength geopolymer concrete incorporating ultrafine fly ash and ultrafine GGBS," *Journal of Environmental Nanotechnology*, 2025, doi: 10.13074/jent.2025.12.2531732.

[9] M. Amran *et al.*, "Long-term durability properties of geopolymer concrete: An in-depth review," 2021, doi: 10.1016/J.CSCM.2021.E00661.

[10] Y. R. Hamed, M. M. Keshta, M. M. Elshikh, A. Elshami, M. H. Matthana, and O. Youssf, "Performance of sustainable geopolymer concrete made of different alkaline activators," *Infrastructures*, 2025, doi: 10.3390/infrastructures10020041.

[11] D. N. Qader, A. W. M. Jamil, A. Bahrami, M. Ali, and K. P. Arunachalam, "A systematic review of metakaolin-based alkali-activated and geopolymer concrete: A step toward green concrete," *REVIEWS ON ADVANCED MATERIALS SCIENCE*, 2025, doi: 10.1515/rams-2024-0076.

[12] E. S. Sunarsih, S. As'ad, A. R. M. Sam, and S. Kristiawan, "The effect of sodium hydroxide molarity on setting time, workability, and compressive strength of fly ash-slag-based geopolymer mortar," *Journal of Physics: Conference Series*, 2023, doi: 10.1088/1742-6596/2556/1/012019.

[13] D. A. K. Rao, M. Yashwanth, C. Karthik, M. Abhijith, and E. Pranay, "Experimental investigation on mechanical and durability properties of geopolymer concrete," *International Journal for Research in Applied Science and Engineering Technology*, 2024, doi: 10.22214/ijraset.2024.60662.

[14] E. Luga, E. Mustafaraj, M. Corradi, and C. Atiş, "Alkali-activated binders as sustainable alternatives to portland cement and their resistance to saline water," *Materials*, 2024, doi: 10.3390/ma17174408.

[15] R. Olayinka, R. Jafari, and M. Fiset, "Shrinkage characteristics of geopolymer concrete: A comprehensive review," *Materials*, 2025, doi: 10.3390/ma18194528.

[16] K. Oliwa, B. Kozub, K. Łoś, P. Łoś, and K. Korniejenko, "Assessment of durability and degradation resistance of geopolymer composites in water environments," *Materials*, 2025, doi: 10.3390/ma18163892.

[17] M. M. Elsebai, "A COMPREHENSIVE REVIEW OF GEOPOLYMER PRODUCTS AS SUSTAINABLE MATERIALS FOR LEED CERTIFICATION COMPLIANCE," *Journal of Al-Azhar University Engineering Sector*, 2025, doi: 10.21608/auej.2025.388454.1848.

[18] L. B. Gudeta, Z. M. Asamenew, and Z. S. Akalu, "Development of ambient-cured geopolymer concrete: Investigating bottom ash as a sustainable alternative to natural river sand," *Advances in Materials Science and Engineering*, 2026, doi: 10.1155/amse/3444514.

[19] D. Tjandra, M. M. C. Sengke, W. Wangidjaja, and Juliastuti, "Sustainable tropical housing design using fly ash geopolymer concrete: An embodied carbon analysis," *IOP Conference Series: Earth and Environment*, 2025, doi: 10.1088/1755-1315/1564/1/012035.

[20] Z. Zhang, Y. Lei, J. Y. R. Liew, M. Liu, G. Wong, and H. Du, "Embodied carbon saving potential of using recycled materials as cement substitute in singapore's buildings," *npj Materials Sustainability*, 2024, doi: 10.1038/s44296-024-00032-w.

[21] S. Sathvik *et al.*, "Evaluating the potential of geopolymer concrete as a sustainable alternative for thin white-topping pavement," *Frontiers in Materials*, 2023, doi: 10.3389/fmats.2023.1181474.

[22] B. Rihawi, M. M. Maraş, E. Ekinci, and E. Kutlusoy, "Development of novel fiber-reinforced eco-friendly concrete: Application in geopolymer concrete pipes infrastructure systems," *Clean Technologies and Environmental Policy*, 2025, doi: 10.1007/s10098-025-03171-3.

[23] S. Mostak, Md. A. Rauf, and M. M. F. I. Barno, "Sustainable geopolymer concrete using recycled brick dust and fly ash: A strength-based study," *International research journal of innovations in engineering and technology*, 2025, doi: 10.47001/irjiet/2025.909009.

[24] Y. Kong, K. Kurumisawa, C. Tokoro, Z. Li, and S. Chu, "Data-driven inverse mix design for sustainable alkali-activated materials," *Journal of Sustainable Cement-Based Materials*, 2024, doi: 10.1080/21650373.2024.2416962.

[25] N. Y. Ezuldin, S. M. Raoof, A. Alattar, and H. Hamada, "Factors affecting durability properties of GPC: A review," *Research on Engineering Structures and Materials*, 2024, doi: 10.17515/resm2024.145ma0109rv.

[26] S. Balasubramanian, M. Khan, and C. McNally, "Standardisation approaches to assessing cementitious materials for sustainable construction," *Reviews on Advanced Materials Science*, 2026, doi: 10.1515/rams-2025-0219.

[27] N. G. Reddy, V. B. Karikatti, B. Pratap, S. V. Patil, and V. Z. Serjun, "Strength and cost analysis of geopolymer concrete using rice husk ash and GGBS as sustainable cement alternatives," *Scientific Reports*, 2026, doi: 10.1038/s41598-026-43705-3.