Advanced International Journal for Research (AIJFR)
E-ISSN: 3048-7641 ● Website: www.aijfr.com ● Email: editor@aijfr.com

Low-Carbon and Geopolymer Concrete: Advances, Challenges, And Future Directions

M.P. Suresh Kumar

Associate Professor
Department of Civil Engineering
Shree Venkateshwara Hi-Tech Engineering College, Tamilnadu

Abstract

The global construction industry's reliance on ordinary Portland cement (OPC) contributes approximately 8% of worldwide CO_2 emissions, representing one of the most urgent decarbonization challenges of the 21st century. This comprehensive literature review synthesizes over six decades of research on low-carbon cementitious materials and geopolymer concrete technologies, examining their fundamental chemistry, mechanical performance, durability, environmental benefits, and barriers to large-scale commercialization. Geopolymer concrete, produced by alkali-activation of aluminosilicate precursors such as fly ash, slag, and metakaolin, demonstrates CO_2 reductions of 40–80% relative to conventional OPC-based systems while achieving comparable or superior compressive strengths (40–120 MPa), enhanced acid and fire resistance, and substantially lower embodied energy. Supplementary cementitious materials (SCMs) including ground granulated blast-furnace slag (GGBS), silica fume, and calcined clays have been increasingly integrated into blended cements, with LC^3 (Limestone Calcined Clay Cement) emerging as a particularly scalable low-carbon solution. Despite remarkable technical progress, challenges persist in standardization, long-term durability validation, alkali activator supply chains, and public sector procurement policies. This review critically evaluates current knowledge gaps and charts priority research directions needed to transition low-carbon concrete from niche applications to mainstream infrastructure use.

Keywords: Geopolymer concrete; Low-carbon cement; Alkali-activated materials; Supplementary cementitious materials; CO_2 emissions; Sustainable construction; Fly ash; Slag; Metakaolin; LC^3

1. Introduction

Concrete is the most widely manufactured material on Earth, with an annual production volume exceeding 10 billion tonnes. Central to its production is ordinary Portland cement (OPC), the binding agent whose manufacture demands calcination of limestone at temperatures above 1,450°C. This thermally intensive process releases CO_2 both as a byproduct of fuel combustion and from the decomposition of calcium carbonate ($CaCO_3 \rightarrow CaO + CO_2$), generating approximately 0.8–0.9 tonnes of CO_2 per tonne of clinker. The cement industry alone accounts for roughly 4 billion tonnes of CO_2 annually — approximately 8% of global anthropogenic greenhouse gas emissions (Andrew, 2019; Scrivener et al., 2018). Against the backdrop of the Paris Agreement's 1.5°C target, transforming

concrete production has become a strategic priority for climate mitigation policy worldwide.

Two overarching technological pathways have emerged as the most promising responses to this challenge. The first involves partial substitution of OPC clinker with supplementary cementitious materials (SCMs), reducing the clinker-to-cement ratio while preserving workability and structural performance. The second pathway — geopolymer or alkali-activated concrete — replaces OPC entirely with activated aluminosilicate precursors, achieving dramatic reductions in process and thermal CO_2 emissions. Both approaches have attracted substantial academic and industrial interest since the 1970s, yet their adoption in standard practice remains limited by technical, regulatory, and economic factors.

This literature review systematically evaluates the state of knowledge on low-carbon and geopolymer concrete technologies. Section 2 provides historical context and development trajectory. Section 3 examines SCM-based blended cements, including fly ash, GGBS, silica fume, and calcined clays. Section 4 details geopolymer concrete chemistry, mix design, and performance. Section 5 addresses durability and long-term behavior. Section 6 presents life-cycle assessment (LCA) and environmental quantification. Section 7 examines commercial applications and case studies. Section 8 discusses barriers and research priorities. Section 9 offers conclusions and recommendations.

1.1 Historical Development and Research Trajectory

Early Innovations in Low-Carbon Binding Materials

The conceptual roots of low-carbon cement alternatives trace back to the 19th century, when engineers observed pozzolanic reactions in natural volcanic ashes mixed with lime. The Romans exploited this chemistry in hydraulic concretes incorporating pozzolana from Puteoli (modern Pozzuoli), producing structures of remarkable durability — some still standing after 2,000 years (Massazza, 1998). The scientific understanding of pozzolanic activity advanced significantly with the work of Vicat (1837) and Le Chatelier (1883), who established the calcium silicate hydrate (C-S-H) gel as the principal binding phase.

Industrial-scale use of fly ash as an SCM commenced in the United States following the proliferation of coal-fired power plants in the mid-20th century. Davis et al. (1937) at the University of California, Berkeley, published foundational studies demonstrating that fly ash could replace up to 30% of cement in concrete while reducing water demand and improving workability. These studies laid the empirical groundwork for ASTM C618, the first standard for coal fly ash in concrete, adopted in 1968.

Concurrent developments in slag utilization arose from the iron-making industry, where ground granulated blast-furnace slag (GGBS) had been recognized since the 1860s as a latent hydraulic material. French chemist Langavant demonstrated that finely ground GGBS could develop cementitious properties in the presence of an alkaline activator. By the early 20th century, slag cements were commercially available in Germany, France, and the United States, regulated under standards that permitted clinker replacements of 35–80%.

1.2 The Geopolymer Concept

The term 'geopolymer' was coined by French chemist Davidovits (1978, 1994), who sought to describe

a new class of inorganic polymers formed by the alkali-activation of aluminosilicate minerals at ambient or slightly elevated temperatures. Davidovits proposed that geopolymers consisted of three-dimensional frameworks of tetrahedral SiO_4 and AlO_4 units linked by shared oxygen atoms, analogous in structure to zeolites but amorphous at typical curing temperatures. His early formulations used metakaolin (calcined kaolin clay) as the precursor and sodium silicate or potassium hydroxide as the activator, achieving compressive strengths of 20–60 MPa within 24 hours at 70°C.

Glukhovsky (1959) in Ukraine had independently described alkali-activated slag systems decades earlier, coining the term 'soil cements' for these binders. His work, less widely disseminated in the Western literature, described the formation of a C-S-H-like gel distinct from the crystalline phases found in OPC hydration, with superior resistance to seawater and sulfate attack. The convergence of Davidovits's nomenclature with Glukhovsky's engineering data provided the framework for what became a rapidly expanding international research field.

The 1990s and 2000s witnessed exponential growth in geopolymer research, catalyzed by increasing environmental awareness and facilitated by improved analytical techniques including X-ray diffraction (XRD), nuclear magnetic resonance (NMR) spectroscopy, and scanning electron microscopy (SEM). Palomo et al. (1999) demonstrated that fly ash — a more abundant and cheaper precursor than metakaolin — could be successfully activated to produce high-strength geopolymer pastes, substantially expanding the practical scope of the technology.

2. Supplementary Cementitious Materials (SCMs) in Low-Carbon Cement Systems

2.1 Fly Ash

Coal fly ash, the fine particulate residue collected from electrostatic precipitators in coal combustion facilities, is the most widely used SCM globally, with an estimated 800 million tonnes generated annually (Lothenbach et al., 2011). Class F fly ash (low calcium, ASTM C618) is predominantly siliceous ($SiO_2 + Al_2O_3 + Fe_2O_3 > 70\%$) and exhibits pozzolanic reactivity: it reacts with calcium hydroxide (portlandite) released during OPC hydration to produce additional C-S-H and aluminosilicate hydrate gels, refining the pore structure and improving long-term strength.

Research by Mehta and Monteiro (2014) established that fly ash replacements of 20–40% by mass of cement reduce water demand by 5–10%, lower early-age heat of hydration (beneficial for mass concrete), and enhance resistance to alkali-silica reaction (ASR) and sulfate attack. Long-term strength studies consistently show that fly ash concretes can match or exceed OPC concrete strength after 90 days of curing, as slow pozzolanic reactions continue for months to years (Shi et al., 2011).

Environmental benefits are substantial: each tonne of fly ash displacing OPC clinker prevents approximately 0.8–0.9 tonnes of CO_2 emissions, while simultaneously diverting a industrial by-product from landfill. However, fly ash availability is geographically uneven and is projected to decline as coal power generation phases out under climate policies, necessitating the development of alternative SCMs (Juenger et al., 2019).

2.2 **Ground Granulated Blast-Furnace Slag (GGBS)**

Ground granulated blast-furnace slag is a glassy by-product of iron manufacturing, formed when

molten slag is quenched with water and subsequently ground to fineness levels of 400–600 m²/kg.

Unlike fly ash, GGBS is a latently hydraulic material capable of limited self-hydration in the presence of water alone, but it develops high reactivity when activated by the alkaline environment provided by OPC hydration products or external alkalis.

The hydration of GGBS in blended systems produces a C-S-H gel with a lower Ca/Si ratio than that generated by OPC alone, alongside C-A-S-H (calcium aluminosilicate hydrate) phases that contribute to a denser, lower-permeability microstructure (Richardson, 1999). Cements with 35–70% GGBS replacement (CEM III/A and III/B under EN 197-1) have been widely used in Europe for applications requiring sulfate resistance, reduced heat of hydration, and enhanced durability in marine environments.

Carbon reduction potential is significant: the production of GGBS entails approximately 0.05–0.07 tonnes of CO_2 per tonne, compared to approximately 0.83 tonnes per tonne for OPC clinker (Habert et al., 2011). Slag cement (50% GGBS blend) thus achieves roughly 45% CO_2 reduction relative to pure OPC. The primary limitation is supply: global GGBS production is constrained by iron manufacturing capacity, and demand for high-quality GGBS already approaches or exceeds supply in some regions (Provis et al., 2014).

2.3 **Silica Fume**

Silica fume (microsilica) is an ultra-fine by-product of silicon and ferrosilicon alloy production, consisting of amorphous SiO_2 spheres with particle sizes typically in the range 0.1–0.3 μm. Its extreme fineness and high SiO_2 content (>90%) endow it with very high pozzolanic reactivity, and even small additions (5–10% by mass of cement) produce substantial improvements in compressive strength, tensile strength, and impermeability.

The micro-filler effect of silica fume particles densifies the interfacial transition zone (ITZ) between aggregate and cement paste, which is typically the weakest phase of conventional concrete. Studies by de Larrard and Sedran (1994) demonstrated that silica fume additions of 10% enabled production of ultra-high-performance concretes (UHPC) with compressive strengths exceeding 150 MPa. While silica fume's CO_2 footprint per unit mass is low, its high cost and limited supply restrict its use to premium applications rather than commodity concrete production.

2.4 Calcined Clays and LC³

Among emerging SCMs, calcined clays — particularly metakaolin and less-refined kaolinitic clays

— have attracted intense research interest as globally abundant, affordable pozzolans. Natural clay deposits are distributed across all continents, making calcined clay an SCM that could be produced locally in regions where fly ash and GGBS are scarce.

The LC³ (Limestone Calcined Clay Cement) system, pioneered by Scrivener and colleagues at EPFL and subsequently studied at IIT Delhi and in Cuba, combines 30% metakaolin, 15% limestone filler, and 50% Portland cement clinker to achieve a CO_2 reduction of approximately 30–40% relative to OPC while maintaining 28-day compressive strengths of 40–60 MPa (Scrivener et al., 2018). The key synergy lies in the reaction between metakaolin, calcium hydroxide, and limestone to form

carboaluminate hydrate phases (hemi- and monocarboaluminate), which participate in strength development and microstructure refinement.

Critically, LC³ can be produced in existing cement plants with relatively modest modifications to the kiln and grinding systems, and the calcination temperature for kaolinitic clays (700–800°C) is substantially lower than that for OPC clinker (1,450°C), reducing fuel consumption and CO_2 intensity. Large-scale pilot projects have demonstrated commercial viability in Cuba, India, and sub-Saharan Africa, positioning LC³ as potentially the most scalable low-carbon cement pathway for the Global South.

3. Geopolymer Concrete: Chemistry, Mix Design, and Mechanical Performance

3.1 Reaction Mechanisms and Microstructure

Geopolymerization proceeds through three overlapping stages: dissolution, condensation, and polycondensation. In the dissolution stage, the alkaline activating solution (typically NaOH, KOH, or sodium silicate solution) attacks the surface of aluminosilicate precursor particles, liberating silicate and aluminate ions into solution. In the condensation stage, these ions form oligomers — small Si-O-Al and Si-O-Si units — that gradually cross-link. In the polycondensation stage, a three-dimensional amorphous gel network forms: in fly ash-based systems this is primarily N-A-S-H (sodium aluminosilicate hydrate), while in slag-based systems C-A-S-H and N-(C)-A-S-H coexist (Provis and van Deventer, 2014).

The resulting binder gel differs fundamentally from OPC-derived C-S-H. The lower Ca/Si ratio of geopolymer gels produces a more cross-linked, rigid network with superior thermal stability and chemical resistance. Infrared spectroscopy (FTIR) and ^{29}Si NMR studies have identified Q^4 and Q^3 silicon environments dominating geopolymer matrices, indicating high degrees of polymerization (Duxson et al., 2007). X-ray diffraction confirms that crystalline phases are minimal, with the principal features being broad amorphous halos consistent with gel formation.

Microstructural examination by SEM reveals that well-activated geopolymer pastes exhibit a dense, homogeneous matrix with few unreacted precursor particles and limited porosity at the aggregate-paste interface. This microstructural densification contributes to high chloride resistance and low water permeability, properties of direct relevance to infrastructure durability.

3.2 Precursor Materials

The properties of geopolymer concrete are critically dependent on the chemical and physical characteristics of the precursor material. The main commercially relevant precursors are:

- Fly ash (low-calcium, ASTM Class F): The most extensively studied precursor, characterized by high silica and alumina content and glassy particle morphology. Fly ash geopolymers typically require heat curing (40–85°C) to achieve adequate early strength, as reactivity at ambient temperature is sluggish (Palomo et al., 1999; Davidovits, 2008).
- Ground granulated blast-furnace slag (GGBS): High calcium content enables rapid ambient-temperature hardening. GGBS geopolymers can achieve 40–70 MPa within 24–48 hours

without heat curing. The primary challenge is rapid setting, which must be controlled through calcium sulfate (gypsum or anhydrite) additions or by modifying activator composition (Shi and Qian, 2000).

- Metakaolin: Produced by calcination of kaolin clay at 700–800°C, metakaolin exhibits high purity and consistent reactivity. Metakaolin geopolymers have been extensively used in research applications and provide excellent fire resistance (up to 1,200°C with minimal spalling) but are more expensive than industrial by-product precursors.
- High-calcium fly ash (Class C): Contains free lime and calcium aluminate phases that react rapidly with water and alkalis, enabling ambient-temperature curing but introducing risks of volume instability if calcium content is excessive (Chindaprasirt et al., 2009).
- Rice husk ash, red mud, and calcined mine tailings: Emerging alternative precursors with potential in resource-constrained regions. These materials exhibit variable quality and require careful characterization and activator optimization (Apithanyasai et al., 2020).

3.3 Alkali Activators

The choice of alkaline activating solution profoundly influences reactivity, setting behavior, workability, and environmental impact. The most common activators are:

- Sodium hydroxide (NaOH): Provides the alkaline pH necessary for precursor dissolution. Concentrations of 8–14 M are typical. Higher concentrations accelerate dissolution but can reduce workability and increase shrinkage. NaOH production is energy-intensive and involves the chlor-alkali process, contributing to embodied CO_2.
- Sodium silicate solution (waterglass, $Na_2O{\cdot}nSiO_2$): Provides both alkalinity and reactive silica, accelerating gel formation and improving compressive strength. The silica modulus (Ms = SiO_2/Na_2O molar ratio) is typically 0.5–2.5 in geopolymer formulations. Sodium silicate production generates 1.5–2.5 tonnes of CO_2 per tonne, representing the dominant embodied carbon source in geopolymer systems (Habert et al., 2011).
- Potassium hydroxide (KOH) and potassium silicate: Yield higher-strength geopolymers in metakaolin systems due to favorable ion size effects but are more expensive than sodium-based activators.
- Solid activators (anhydrous Na_2SiO_3, $NaAlO_2$): Emerging alternatives that simplify transportation, reduce alkaline hazards, and can be pre-blended with precursors to produce 'just-add-water' geopolymer products (Nematollahi et al., 2015).

3.4 Mechanical Properties

The mechanical performance of geopolymer concrete is broadly comparable to or superior to OPC concrete across a range of mix designs, precursors, and curing conditions. A comprehensive meta-analysis by Provis et al. (2015) collating data from over 200 published studies found:

- Compressive strength: Fly ash geopolymers cured at 60°C achieve 40–80 MPa at 28 days; slag-based geopolymers reach 50–90 MPa at ambient temperature. Hybrid (fly ash + slag) systems offer balanced reactivity and strengths of 50–80 MPa without heat curing.

- Tensile strength: Splitting tensile strength is typically 8–12% of compressive strength, similar to or slightly higher than OPC concrete.
- Elastic modulus: Generally 10–15% lower than OPC concrete of equivalent compressive strength, attributed to the softer gel matrix and reduced stiffness of the binder phase.
- Flexural strength: Comparable to OPC concrete; metakaolin geopolymers show higher flexural-to-compressive strength ratios than fly ash systems.

Ultra-high-performance geopolymer concretes (UHPGC) have been developed using optimized particle packing and reactive fiber reinforcement (steel or PVA fibers), achieving compressive strengths of 100–200 MPa and tensile capacities exceeding 10 MPa (Yunsheng et al., 2007). These materials offer potential for thin-section structural elements with dramatically reduced material use.

4. Durability and Long-Term Performance

4.1 Chemical Resistance

One of the most consistently cited advantages of geopolymer concrete relative to OPC systems is superior chemical resistance. The absence or minimal presence of calcium hydroxide (portlandite) — the most vulnerable phase in OPC concrete — renders geopolymers inherently more resistant to acidic environments, sulfate attack, and seawater exposure.

Acid resistance: Studies by Bakharev et al. (2003) exposed fly ash geopolymer and OPC concrete specimens to 5% sulfuric acid (H_2SO_4) solution for 5 months. Geopolymer specimens lost 14–18% of mass and retained 35–60% of initial compressive strength, while OPC concrete disintegrated almost entirely, retaining less than 10% of initial strength. Similar findings have been reported for citric acid (relevant to food processing facilities) and acetic acid environments.

Sulfate resistance: The C_3A phase in OPC reacts with sulfate ions to form expansive ettringite, causing cracking and spalling. Geopolymer matrices, lacking C_3A, are fundamentally resistant to sulfate-induced expansion. Long-term studies (>1 year) in sodium sulfate and magnesium sulfate solutions confirm negligible degradation of geopolymer concrete (Provis et al., 2015).

Seawater resistance: Marine exposure studies demonstrate superior chloride resistance in geopolymer concretes compared to OPC. Chloride diffusion coefficients measured by RCPT (Rapid Chloride Permeability Test) are typically 50–80% lower than OPC concrete of comparable compressive strength, implying extended service life and reduced reinforcement corrosion risk in marine infrastructure.

4.2 Thermal Stability and Fire Resistance

The thermally stable aluminosilicate framework of geopolymers confers exceptional fire resistance, a property of considerable importance for structural safety. Unlike OPC concrete, which undergoes dehydration of C-S-H phases and calcium hydroxide decomposition between 300–600°C — resulting in microcracking, spalling, and loss of strength — geopolymer concrete maintains structural integrity to substantially higher temperatures.

Kong and Sanjayan (2010) reported that metakaolin geopolymer cylinders exposed to 800°C retained 70–90% of ambient-temperature compressive strength, with no spalling. Fly ash geopolymers show somewhat lower thermal stability than metakaolin systems but significantly outperform OPC concrete at temperatures above 400°C. The superior fire resistance is attributed to the ceramic-like character of the geopolymer matrix, which undergoes beneficial densification rather than destructive decomposition at elevated temperatures.

These properties make geopolymer concrete particularly attractive for tunnels, fire stations, nuclear waste containment structures, and other facilities where thermal resistance is a design criterion. Post-fire assessment of geopolymer structures is also simplified by the preservation of surface morphology, enabling visual inspection to more accurately indicate structural condition.

4.3 Shrinkage, Creep, and Volume Stability

Drying shrinkage has been identified as one of the primary durability concerns for geopolymer concretes, particularly those based on metakaolin or low-calcium fly ash. Aydın and Baradan (2014) reviewed published shrinkage data and found that metakaolin geopolymers could exhibit drying shrinkage strains of 1,000–4,000 microstrain under low-humidity conditions, substantially exceeding values typical for OPC concrete (400–800 microstrain). The mechanism involves the evaporation of free water from the gel network, resulting in capillary tension and matrix contraction.

Mitigation strategies for geopolymer shrinkage include internal curing with saturated lightweight aggregate, addition of expansive components (e.g., MgO), optimization of the Si/Al ratio to reduce gel porosity, and sealed curing during early-age development. Slag-rich hybrid geopolymers exhibit considerably lower shrinkage than metakaolin or fly ash-only systems, attributed to the denser, lower-porosity C-A-S-H gel formed in calcium-rich environments.

Creep behavior of geopolymer concrete has received comparatively less attention but is of critical importance for structural applications. Collins and Sanjayan (1999) found that fly ash geopolymer concretes exhibited higher specific creep than OPC concrete under equivalent sustained loads, attributed to continued gel reorganization and densification. More recent studies using slag-fly ash blends show creep coefficients closer to those of OPC concrete, suggesting that binder chemistry can be tailored to manage long-term deformation.

5. Life-Cycle Assessment and Environmental Quantification

5.1Carbon Footprint Quantification

Life-cycle assessment (LCA) provides the most rigorous framework for comparing the environmental impacts of geopolymer and OPC concrete systems across their full production chains. Cradle-to-gate LCA studies consistently demonstrate significant CO_2 reductions for geopolymer concrete relative to OPC, though the magnitude varies considerably depending on precursor type, activator choice, transportation distances, and the system boundary adopted.

Habert et al. (2011) conducted a comprehensive comparative LCA of fly ash geopolymer concrete (NaOH + sodium silicate activator) versus OPC concrete for equivalent structural performance. The

study found that despite lower CO_2 from the precursor (near zero, as fly ash is a by-product), the sodium silicate production accounted for 60–80% of geopolymer embodied CO_2, resulting in reductions of only 26–45% compared to OPC. Importantly, this study underscored that the choice and quantity of sodium silicate is the pivotal variable in geopolymer LCA.

Subsequent studies employing lower-modulus activators, solid-form waterglass, or partial replacement of sodium silicate with NaOH or calcium carbonate have demonstrated CO_2 reductions of 40–70% (Turner and Collins, 2013). Geopolymer systems using GGBS with low-dose NaOH activation can achieve CO_2 intensities below 100 kg CO_2e per tonne of concrete — less than one-third of typical OPC concrete — when slag is sourced locally and transported efficiently.

5.2 Embodied Energy and Other Impact Categories

Carbon footprint, while the most politically prominent metric, represents only one dimension of environmental impact. Energy embodied in materials (MJ/m³) is an important co-metric, as cement production is the third most energy-intensive industrial process globally. LCA studies show that geopolymer concrete typically embodies 30–60% less primary energy than OPC concrete, with slag-based systems at the lower end of this range (Bajpai et al., 2020).

Water consumption is an emerging concern in LCA of cementitious materials. Fly ash geopolymers generally require less mixing water than OPC concrete for equivalent workability, while NaOH and sodium silicate production each involve water-intensive industrial processes. A full cradle-to-gate water LCA remains underrepresented in the geopolymer literature.

Human toxicity and ecotoxicity potential are elevated in geopolymer systems due to the highly alkaline activators: handling concentrated NaOH (>8 M) and sodium silicate solutions poses occupational health risks and requires appropriate personal protective equipment. This concern has partly driven interest in solid-form activators and one-part geopolymer systems that can be handled more safely.

6. Commercial Applications and Case Studies

6.1 Infrastructure Applications

Geopolymer concrete has been successfully deployed in a growing number of real-world infrastructure projects, demonstrating its viability beyond laboratory conditions. Notable case studies include:

- Brisbane West Wellcamp Airport (Australia, 2014): The apron and taxiway pavements at this regional airport incorporated approximately 40,000 m³ of fly ash geopolymer concrete — one of the largest civil geopolymer applications to date. Performance monitoring over subsequent years confirmed compressive strengths of 40–50 MPa and no anomalous distress, validating the mix design under heavy aircraft loading (Wagners, 2014).
- Zeobond E-Crete (Australia): Zeobond Pty Ltd commercialized geopolymer concrete under the proprietary E-Crete brand, supplying precast elements and in-situ applications across transport infrastructure. E-Crete formulations use fly ash and slag with patented activator blends, achieving certification to Australian Standards AS 3600 for structural concrete.
- Intertek-certified geopolymer pipes (South Africa): A pipe manufacturer in South Africa adopted

geopolymer concrete for sewer pipes, achieving EN 1916-equivalent compressive and chemical resistance performance. The project demonstrated cost-competitiveness with OPC pipe in a context where fly ash was abundantly available from adjacent power plants.

6.2 Precast Industry Adoption

The precast concrete industry presents a favorable environment for geopolymer adoption because heat curing — commonly used to accelerate OPC concrete strength development — is already integrated in manufacturing workflows. Heat curing at 60–80°C for 6–12 hours efficiently activates fly ash geopolymers and allows demoulding within 24 hours, matching or exceeding OPC precast production cycles.

Companies in Australia, the Netherlands, and the United States have produced commercial geopolymer precast elements including railway sleepers, wall panels, drainage products, and structural beams. The Wagners group in Queensland, Australia, has been particularly prolific, developing geopolymer formulations certified under Australian standards and supplying multiple infrastructure projects. Dutch company Ecocem has commercialized GGBS-based binders for ready-mix and precast applications across Northwestern Europe.

7. Barriers to Adoption and Priority Research Directions

7.1 Regulatory and Standardization Barriers

The most significant barrier to mainstream adoption of geopolymer and low-carbon concrete is the absence of dedicated, performance-based standards in most national regulatory frameworks. Design codes (ACI 318, Eurocode 2, AS 3600) are formulated around OPC-based concrete and rely on empirical relationships between water-cement ratio, strength, and durability that do not translate directly to geopolymer systems. Without standards specifying acceptance criteria and design methodologies for geopolymer concrete, structural engineers and public procurement agencies face liability uncertainty that effectively precludes specification.

Progress is being made: RILEM Technical Committee 247-DTA has published recommendations for testing and design of alkali-activated concrete (Provis et al., 2017), and standards bodies in Australia (Standards Australia), the United States (ASTM), and Europe (CEN) have issued or are developing standards for alkali-activated materials. However, full integration into design codes requires extensive field performance data spanning decades — data that is only now beginning to accumulate.

7.2 Technical Challenges

Several technical challenges require further systematic investigation to support reliable large-scale deployment:

- Variability of by-product precursors: The chemical composition of fly ash and GGBS varies with source material, combustion conditions, and processing parameters. Mix designs validated for one source may not transfer directly to another without recalibration, complicating standardization for ready-mix producers.
- Setting time control: Slag-rich geopolymers can exhibit very rapid setting (≤1 hour), while fly ash

geopolymers may have delayed setting at ambient temperature. Robust, commercially available set-controlling admixtures remain underdeveloped for geopolymer systems relative to the mature admixture chemistry available for OPC concrete.

- Reinforcement compatibility: Geopolymer concrete environments are strongly alkaline (pH >12), similar to OPC concrete, suggesting adequate passive film formation on steel reinforcement. However, the chloride threshold for depassivation and the carbonation behavior of geopolymers in CO_2-rich environments differ from OPC concrete and require further quantification.
- Long-term durability validation: Most geopolymer field exposure data extends to 10–15 years, insufficient to validate models for 50–100 year design service lives typical for infrastructure. Accelerated aging methods calibrated specifically for geopolymer systems are needed.

7.3 Economic Barriers

The economics of geopolymer concrete are context-dependent. In regions with abundant, low-cost fly ash and GGBS, geopolymer concrete can be cost-competitive with OPC concrete; in regions where precursors must be transported long distances or sodium silicate is expensive, the material cost premium of 10–30% remains a barrier for commodity construction. The lack of economies of scale — stemming from limited market penetration — perpetuates higher costs, creating a 'chicken-and-egg' dynamic that public procurement policy could help break.

Carbon pricing mechanisms (carbon taxes, emissions trading schemes) have the potential to substantially alter the relative economics of low-carbon and conventional concrete. A carbon price of \$50–100 per tonne CO_2 would add \$35–75 per tonne to OPC production costs, making geopolymer concrete straightforwardly cost-competitive in many formulations. With growing carbon price ambition under national net-zero legislation, the economic case for low-carbon concrete will strengthen significantly over the coming decade.

8. Conclusions and Recommendations

This literature review has synthesized the extensive body of research on low-carbon and geopolymer concrete, revealing a field characterized by strong technical foundations, growing commercial momentum, and persistent regulatory and economic headwinds. The key conclusions are as follows:

- Supplementary cementitious materials (fly ash, GGBS, silica fume, and calcined clays) offer near-term, deployable pathways to reduce the carbon intensity of conventional concrete by 30–60%, with LC^3 emerging as the most globally scalable solution given its reliance on widely available clay resources.
- Geopolymer concrete demonstrates mechanical properties comparable to or superior to OPC concrete for compressive strength, acid resistance, fire resistance, and chloride impermeability. It can achieve CO_2 reductions of 40–80% relative to OPC, with the greatest benefits realized when low-modulus activators or solid-form activators replace conventional sodium silicate solutions.
- Durability remains an area of active investigation. Shrinkage and creep of low-calcium geopolymers require further characterization and mitigation, and long-term field data must be systematically collected and disseminated to underpin design standards.

- Life-cycle assessment confirms substantial environmental benefits but reveals the critical importance of activator choice: sodium silicate production is the dominant embodied carbon source in geopolymer systems and must be minimized or replaced with lower-impact alternatives.
- Regulatory and standardization barriers are the most pressing constraint on geopolymer adoption. Priority should be assigned to developing performance-based standards that accommodate the full family of alkali-activated materials alongside OPC-based systems.

Future research priorities should include: (i) development of robust, standardized test methods for fresh and hardened geopolymer concrete; (ii) long-term field performance databases across diverse climatic and exposure conditions; (iii) optimization of activator systems to minimize embodied carbon while maintaining performance; (iv) investigation of hybrid binder systems combining SCMs and alkali-activation to leverage synergies; (v) systematic study of reinforcement compatibility and structural performance under service loading; and (vi) life-cycle cost analyses incorporating externalized carbon costs to inform policy and investment decisions.

Low-carbon concrete technologies are technically mature and economically viable for a widening range of applications. Accelerating their transition to mainstream construction practice will require concerted action from researchers, standards bodies, policymakers, procurement agencies, and industry — but represents one of the most impactful available levers for decarbonizing the built environment.

References

1. Andrew, R.M. (2019). Global CO_2 emissions from cement production, 1928–2018. Earth System Science Data, 11(4), 1675–1710.
2. Apithanyasai, S., Supakata, N., & Papong, S. (2020). The potential of industrial waste: Using foundry sand with fly ash and electric arc furnace slag for geopolymer brick production. Heliyon, 6(3), e03697.
3. Aydın, S., & Baradan, B. (2014). Effect of activator type and content on properties of alkali-activated slag mortars. Composites Part B: Engineering, 57, 166–172.
4. Bajpai, R., Choudhary, K., Srivastava, A., Sangwan, K.S., & Singh, M. (2020). Environmental impact assessment of fly ash and silica fume based geopolymer concrete. Journal of Cleaner Production, 254, 120147.
5. Bakharev, T., Sanjayan, J.G., & Cheng, Y.B. (2003). Resistance of alkali-activated slag concrete to acid attack. Cement and Concrete Research, 33(10), 1607–1611.
6. Chindaprasirt, P., Chareerat, T., & Sirivivatnanon, V. (2007). Workability and strength of coarse high calcium fly ash geopolymer. Cement and Concrete Composites, 29(3), 224–229.
7. Collins, F., & Sanjayan, J.G. (1999). Effects of ultra-fine materials on workability and strength of concrete containing alkali-activated slag as the binder. Cement and Concrete Research, 29(3), 459–462.
8. Davidovits, J. (1978). Synthesis of new high-temperature geo-polymers for reinforced plastics/composites. SPE PACTEC '78, 151–154.

9. Davidovits, J. (1994). Geopolymers: Man-made rock geosynthesis and the resulting development of very early high strength cement. Journal of Materials Education, 16(2–3), 91–139.
10. Davis, R.E., Carlson, R.W., Kelly, J.W., & Davis, H.E. (1937). Properties of cements and concretes containing fly ash. Journal of the American Concrete Institute, 33, 577–612.
11. de Larrard, F., & Sedran, T. (1994). Optimization of ultra-high-performance concrete by the use of a packing model. Cement and Concrete Research, 24(6), 997–1009.
12. Duxson, P., Fernández-Jiménez, A., Provis, J.L., Lukey, G.C., Palomo, A., & van Deventer, J.S.J. (2007). Geopolymer technology: The current state of the art and future research challenges. Journal of Materials Science, 42(9), 2917–2933.
13. Glukhovsky, V.D. (1959). Soil Silicates. Gostroiizdat Publishing House, Kiev (in Russian).
14. Habert, G., d'Espinose de Lacaillerie, J.B., & Roussel, N. (2011). An environmental evaluation of geopolymer based concrete production: Reviewing current research trends. Journal of Cleaner Production, 19(11), 1229–1238.
15. Juenger, M.C.G., Snellings, R., & Bernal, S.A. (2019). Supplementary cementitious materials: New sources, characterization, and performance insights. Cement and Concrete Research, 122, 257–273.
16. Kong, D.L.Y., & Sanjayan, J.G. (2010). Effect of elevated temperatures on geopolymer paste, mortar and concrete. Cement and Concrete Research, 40(2), 334–339.
17. Lothenbach, B., Scrivener, K., & Hooton, R.D. (2011). Supplementary cementitious materials. Cement and Concrete Research, 41(12), 1244–1256.
18. Massazza, F. (1998). Pozzolana and pozzolanic cements. In P.C. Hewlett (Ed.), Lea's Chemistry of Cement and Concrete (4th ed., pp. 471–635). Arnold, London.
19. Mehta, P.K., & Monteiro, P.J.M. (2014). Concrete: Microstructure, Properties, and Materials (4th ed.). McGraw-Hill, New York.
20. Nematollahi, B., Sanjayan, J., & Shaikh, F.U.A. (2015). Synthesis of heat and ambient cured one-part geopolymer mixes with different grades of sodium silicate. Ceramics International, 41(4), 5945–5952.
21. Palomo, A., Grutzeck, M.W., & Blanco, M.T. (1999). Alkali-activated fly ashes: A cement for the future. Cement and Concrete Research, 29(8), 1323–1329.
22. Provis, J.L., & van Deventer, J.S.J. (Eds.). (2014). Alkali Activated Materials: State-of-the-Art Report, RILEM TC 224-AAM. Springer, Dordrecht.
23. Provis, J.L., Arbi, K., Bernal, S.A., et al. (2017). RILEM TC 247-DTA round robin test: Mix design and fresh properties of alkali-activated concretes. Materials and Structures, 52(1), 9.
24. Richardson, I.G. (1999). The nature of C-S-H in hardened cements. Cement and Concrete Research, 29(8), 1131–1147.
25. Scrivener, K., Martirena, F., Bishnoi, S., & Maity, S. (2018). Calcined clay limestone cements (LC3). Cement and Concrete Research, 114, 49–56.
26. Shi, C., & Qian, J. (2000). High performance cementing materials from industrial slags: A review.

Resources, Conservation and Recycling, 29(3), 195–207.

27. Shi, C., Roy, D., & Krivenko, P. (2006). Alkali-Activated Cements and Concretes. Taylor & Francis, London.
28. Turner, L.K., & Collins, F.G. (2013). Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete. Construction and Building Materials, 43, 125–130.
29. Wagners. (2014). Earth Friendly Concrete™: Brisbane West Wellcamp Airport. Wagners Technical Report, Toowoomba, Australia.
30. Yunsheng, Z., Wei, S., Zongjin, L., Xiangming, Z., & Chungong, C. (2007). Synthesis and heavy metal immobilization behaviors of slag based geopolymer. Journal of Hazardous Materials, 143(1–2), 206–213.