JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

EVOLUTION OF MATERIALS IN LOW-CARBON GEOPOLYMER CONCRETE – A COMPREHENSIVE REVIEW

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Abstract : *The construction sector is increasingly seeking low-carbon cementitious materials to reduce the environmental impacts associated with conventional Ordinary Portland Cement (OPC) production. Geopolymer concrete (GPC), produced through the alkali activation of aluminosilicate-rich materials, has emerged as a promising alternative because of its potential to utilize industrial, agricultural, and mineral wastes while providing competitive mechanical and durability performance. However, the sustainability and engineering performance of GPC are strongly dependent on the type, composition, and proportion of constituent materials. This review presents a comprehensive assessment of the evolution of materials used in low-carbon geopolymer concrete, tracing the transition from conventional precursors and alkaline activators toward waste-derived, renewable, and advanced materials.*

The review systematically examines major aluminosilicate precursors, including fly ash, ground granulated blast-furnace slag, metakaolin, rice husk ash, zeolite, mine-derived materials, and other industrial and agricultural waste-derived precursors. Particular attention is given to their chemical composition, replacement levels, calcium content, geopolymerization characteristics, and influence on compressive strength, tensile and flexural performance, durability, and microstructure. The evolution of alkaline activation systems from conventional sodium hydroxide and sodium silicate toward sodium carbonate, waste-derived alkalis, and one-part activators is also discussed. In addition, emerging sustainable additives such as biochar, nano-silica, graphene oxide, natural and synthetic fibres, and other functional materials are critically evaluated for their role in improving mechanical performance, pore structure, durability, carbon sequestration potential, and resource efficiency. Recent studies indicate that alternative activators and waste-derived constituents can substantially reduce the environmental burden associated with conventional geopolymer systems, although their performance remains highly dependent on material chemistry, processing conditions, and geographical availability.

Furthermore, the review establishes relationships between material selection, mix-design parameters, curing conditions, mechanical properties, durability, and environmental performance. Particular emphasis is placed on the trade-offs between strength, workability, activator demand, embodied carbon, cost, and long-term durability. The review identifies critical research gaps, including the lack of standardized mix-design methodologies, variability in waste-derived precursor chemistry, limited long-term durability data, dependence on commercially manufactured alkaline activators, and insufficient integration of life-cycle assessment with experimental performance. Finally, future research directions are proposed toward waste-derived precursors, low-carbon activators, bio-based additives, ambient-cured systems, one-part geopolymers, carbon-sequestering materials, and data-driven material optimization, with the aim of developing scalable, economical, durable, and genuinely low-carbon geopolymer concrete for sustainable construction.

***IndexTerms* -** Geopolymer concrete, Low-carbon construction, Aluminosilicate precursors, Alkaline activators, Sustainable additives, Durability, Life-cycle assessment

I. Introduction

1.1 Environmental Impact of Cement Industry

The cement industry is widely recognized as one of the most carbon-intensive sectors in the construction field. Ordinary Portland Cement (OPC) production requires high-temperature clinkerization processes, which consume large quantities of fossil fuels and release significant carbon dioxide emissions through both fuel combustion and limestone calcination. As global urbanization continues to expand, the demand for cement and concrete is increasing rapidly, resulting in a substantial rise in greenhouse gas emissions. Meyer (2009) emphasized that cement manufacturing is a major contributor to global CO_2 emissions and that the concrete industry must undergo transformation to meet sustainability targets (Meyer, 2009).

In addition to CO_2 emissions, cement production also contributes to environmental degradation through the consumption of natural resources, high energy demand, dust generation, and land disturbance caused by raw material extraction. Environmental sustainability assessments have highlighted that reducing clinker content is one of the most effective pathways to lower the environmental footprint of concrete materials (Thomas et al., 2018; Garcia et al., 2019).

Life cycle assessment (LCA) studies further demonstrate that OPC-based concrete exhibits higher embodied carbon compared to alternative binder systems. Shi et al. (2021) reported that geopolymer-based binders derived from industrial by-products can significantly reduce environmental impacts compared to conventional OPC mixtures (Shi et al., 2021). Therefore, the cement sector requires urgent innovation and adoption of alternative materials to address climate change mitigation goals (Ji & Zhang, 2023).

1.2 Need for Low-Carbon Construction

The construction sector plays a crucial role in achieving global climate targets because it accounts for a significant share of energy consumption and carbon emissions throughout the lifecycle of infrastructure. Sustainable development goals and net-zero carbon initiatives demand the adoption of eco-friendly construction materials with reduced embodied carbon. Low-carbon construction aims to minimize greenhouse gas emissions through the utilization of alternative binders, recycled materials, industrial by-products, and improved mix designs.

In recent years, researchers have emphasized the need for low-carbon concrete technologies that can replace OPC partially or completely without compromising structural performance. Nath (2020) stated that low-carbon concrete systems must provide adequate strength, durability, and long-term reliability to be practically adopted in infrastructure development (Nath, 2020). Similarly, Ji and Zhang (2023) reviewed sustainable concrete technologies and concluded that low-carbon mixtures can be developed using supplementary cementitious materials, alkali activation, and waste-derived precursors (Ji & Zhang, 2023).

The concept of sustainable concrete is not limited to reducing emissions; it also includes improving durability and extending service life, thereby lowering the need for frequent repair and reconstruction. Bernal et al. (2018) noted that durable alkali-activated materials have the potential to significantly reduce environmental burdens by offering improved resistance against chemical attack and harsh environmental exposure (Bernal et al., 2018). Hence, low-carbon construction materials represent a vital research area in modern civil engineering.

1.3 Emergence of Geopolymer Technology

Geopolymer technology emerged as a revolutionary alternative to OPC-based binders due to its ability to utilize aluminosilicate-rich precursors activated by alkaline solutions. The concept of geopolymers was first introduced by Davidovits (1991), who described them as inorganic polymeric materials formed by the polycondensation of silica and alumina species, producing hardened binders with strong mechanical and chemical properties (Davidovits, 1991). This discovery laid the foundation for the development of alkali-activated binders and geopolymer concrete systems.

Geopolymer concrete typically employs industrial by-products such as fly ash, slag, metakaolin, and other aluminosilicate wastes, which reduces reliance on limestone-based clinker production. Hardjito and Rangan (2005) conducted pioneering work on low-calcium fly ash-based geopolymer concrete and demonstrated that such systems can achieve high compressive strength, good workability, and improved durability under controlled curing conditions (Hardjito & Rangan, 2005).

Further advancements in geopolymer technology have been extensively documented by Duxson et al. (2007), who described the current state of geopolymer science and highlighted its potential as a low-carbon alternative for construction applications (Duxson et al., 2007). Provis and van Deventer (2014) later provided comprehensive knowledge on alkali-activated materials, discussing reaction mechanisms, microstructural development, and practical implementation in cement replacement systems (Provis & van Deventer, 2014).

The geopolymerization process forms a three-dimensional aluminosilicate network that provides high compressive strength and chemical stability. Fernandez-Jimenez and Palomo (2005) studied alkali-activated fly ash mortars and confirmed that microstructural densification and geopolymer gel formation contribute significantly to strength gain (Fernandez-Jimenez & Palomo, 2005).

Recent studies have expanded geopolymer applications into structural and aggressive exposure environments. Kwasny et al. (2021) reviewed geopolymer concrete suitability for marine structures, emphasizing its resistance to chloride penetration and sulfate attack (Kwasny et al., 2021). Zhang et al. (2024) also critically reviewed durability aspects of low-carbon geopolymer concrete and identified it as a promising material for long-term sustainable infrastructure (Zhang et al., 2024).

Despite its advantages, challenges remain in large-scale adoption, such as activator handling, curing requirements, variability of precursor materials, and lack of standardized codes. Zhang et al. (2020) highlighted that geopolymer concrete has major opportunities but still faces technical and regulatory barriers in mainstream construction (Zhang et al., 2020). Nevertheless, the continuous growth of research in geopolymer science indicates its strong potential for the future of sustainable construction.

1.4 Objectives and Significance of the Review

The main objective of this review paper is to provide a comprehensive overview of the evolution, performance, and sustainability potential of geopolymer concrete as a low-carbon alternative to OPC-based concrete. This review critically evaluates geopolymer binder chemistry, precursor materials, mechanical behavior, durability characteristics, and environmental benefits based on existing research findings.

This review also aims to highlight recent developments in durability performance, long-term structural behavior, and sustainability evaluation methods. Lee et al. (2022) reported that geopolymer concrete exhibits promising long-term performance when exposed to various environmental conditions, making it a suitable candidate for infrastructure applications (Lee et al., 2022). Additionally, durability studies related to carbonation, sulfate exposure, and aggressive environments are crucial for understanding geopolymer suitability in real construction conditions (Ganesan et al., 2017; Garcia-Lastra et al., 2019).

Another important objective is to examine the environmental performance of geopolymer concrete using life cycle assessment frameworks. Studies have shown that geopolymer binders can reduce embodied carbon substantially compared to OPC systems, particularly when industrial by-products are used as precursors (Shi et al., 2021; Palomo et al., 2020). Advanced approaches such as AI-integrated sustainability assessment are also emerging, offering improved predictive accuracy for environmental impact evaluation (Ramesh et al., 2025).

The significance of this review lies in identifying current research gaps, technical challenges, and opportunities for future work toward net-zero construction. Nath and Sarker (2019) stated that geopolymer concrete is rapidly evolving and requires systematic review-based research to strengthen its practical adoption (Nath & Sarker, 2019). Furthermore, Adnan (2025) emphasized that geopolymer concrete represents one of the most promising sustainable alternatives for reducing cement industry emissions, provided that performance consistency and large-scale implementation challenges are addressed (Adnan, 2025).

Overall, this review contributes to sustainable civil engineering by consolidating key research findings, evaluating progress in low-carbon geopolymer concrete, and presenting directions for future innovation and field implementation.

II. Evolution of Geopolymer Technology

Geopolymer technology has evolved significantly over the last few decades, transitioning from laboratory-based heat-cured binder systems to advanced ambient-cured, nano-modified, and bio-based composites. The evolution is largely driven by the need to improve early strength, curing practicality, long-term durability, and environmental sustainability. The development can be categorized into three main stages: early generation, intermediate generation, and advanced generation geopolymers.

2.1 Early Generation Geopolymers

2.1.1 Fly Ash Geopolymers

Early geopolymer research was dominated by fly ash-based binder systems due to the high silica and alumina content of fly ash, which makes it suitable for geopolymerization. Fly ash geopolymers gained attention because they utilize industrial waste and reduce dependence on OPC, offering a low-carbon alternative for construction. High-volume fly ash systems were widely studied for producing geopolymer concrete with good mechanical performance, although curing conditions were often a major limitation. Shi et al. (2020) highlighted that high-volume fly ash-based low-carbon concretes exhibit significant sustainability benefits but may suffer from delayed strength development under ambient conditions (Shi et al., 2020).

High-calcium fly ash systems were also investigated, where calcium plays a critical role in accelerating reaction kinetics and early strength gain. Sakai et al. (2015) reported that high-calcium fly ash can improve the setting and strength performance of geopolymer binders compared to low-calcium fly ash systems, though it may also influence long-term stability and microstructure (Sakai et al., 2015).

2.1.2 Metakaolin Systems

Metakaolin-based geopolymers represent another major early-generation binder system, known for their high reactivity, uniform composition, and superior microstructural formation. Metakaolin is produced by calcination of kaolinite clay and is considered a highly reactive aluminosilicate precursor. Zhang and Fang (2017) reviewed metakaolin geopolymers and concluded that they typically show high early compressive strength and dense microstructures but may involve higher material costs compared to industrial waste precursors (Zhang & Fang, 2017).

Calcined clay-based alkali activated systems have also gained interest due to their availability and controlled mineralogy. Tang et al. (2022) emphasized that calcined clays contribute to improved binder consistency and can serve as promising geopolymer precursors in regions where fly ash or slag availability is limited (Tang et al., 2022).

2.1.3 Heat-Cured Binder Systems

The first-generation geopolymer binders were commonly heat-cured to enhance geopolymerization reactions and achieve higher early strength. Heat curing (typically 60–90°C) accelerates dissolution of silica-alumina species and improves polymer chain formation. However, the requirement of elevated temperature curing limited the practical field application of early geopolymer concrete systems. Abdel-Gawwad et al. (2019) highlighted that curing temperature significantly affects geopolymer gel formation and strength development, and low-temperature curing may lead to incomplete reaction and lower mechanical performance (Abdel-Gawwad et al., 2019).

Thus, although early-generation geopolymers demonstrated strong potential, their reliance on heat curing and controlled conditions restricted their widespread adoption in large-scale construction.

2.2 Intermediate Generation Geopolymers

The intermediate phase of geopolymer development focused on improving field applicability, particularly by achieving ambient curing, faster setting, and enhanced durability through the incorporation of calcium-rich materials and hybrid binder systems.

2.2.1 GGBS Incorporation

The introduction of ground granulated blast furnace slag (GGBS) marked a major breakthrough in geopolymer technology. Slag is rich in calcium and reacts rapidly under alkaline activation, forming calcium-aluminosilicate-hydrate (C-A-S-H) gels in addition to geopolymer gel, thereby improving early strength and reducing curing dependency. Kumar et al. (2017) reviewed slag geopolymer systems and reported that slag incorporation significantly improves mechanical properties and provides better performance under ambient curing compared to fly ash-only systems (Kumar et al., 2017).

Similarly, Anuradha et al. (2021) demonstrated that the slag-to-fly ash ratio strongly influences strength development and microstructure, with higher slag content generally improving early compressive strength and reducing setting time (Anuradha et al., 2021).

2.2.2 Ambient-Cured Systems

Ambient curing is essential for practical geopolymer concrete implementation, especially in large infrastructure projects. The development of ambient-cured geopolymer systems has been achieved through optimizing precursor blends, activator concentration, and incorporating calcium-rich additives. Li et al. (2021) emphasized that optimizing precursor ratios is a critical strategy to ensure consistent strength performance under room temperature curing (Li et al., 2021).

However, precursor variability remains a challenge because fly ash, slag, and other industrial wastes differ significantly depending on source and processing. Yin et al. (2020) noted that precursor source variability can alter reaction kinetics, setting behavior, and final binder properties, affecting both mechanical and durability performance (Yin et al., 2020).

2.2.3 Hybrid Binder Systems

Hybrid geopolymer binders involve blending alkali-activated precursors with small quantities of OPC or calcium-based additives to improve early hydration and compatibility with conventional concrete systems. Such systems aim to bridge the gap between traditional cement-based concrete and geopolymer technology. Chen et al. (2021) reported that incorporating industrial by-products and hybrid blending techniques can enhance workability, strength, and durability, while still achieving significant carbon emission reduction (Chen et al., 2021).

The intermediate generation thus represents the stage where geopolymer concrete began transitioning from research-scale material into a feasible construction alternative.

2.3 Advanced Generation Geopolymers

The advanced generation of geopolymer technology focuses on achieving simplified processing, enhanced performance, and improved sustainability through innovative precursor sources, nano-additives, and bio-based reinforcement strategies.

2.3.1 One-Part Geopolymers

One-part geopolymers, also known as “just add water” geopolymers, are an emerging class of binders where dry activators and precursor powders are premixed, enabling easier handling and safer field implementation. This approach reduces the need for corrosive liquid alkaline solutions and improves practical feasibility for large-scale construction.

Alternative precursor systems such as mine tailings and recycled materials are also being studied to support one-part geopolymer development. Sen et al. (2018) discussed the feasibility of alkali-activated mine tailings as sustainable binder materials, indicating that they can serve as low-carbon alternatives if properly processed and optimized (Sen et al., 2018).

2.3.2 Nano-Modified Geopolymer Systems

Nano-modification has emerged as a major advancement in improving geopolymer microstructure, mechanical strength, and durability. Nano-additives such as nano-silica, nano-alumina, carbon nanotubes, and nano-clays enhance nucleation sites and densify geopolymer gel networks. Gupta et al. (2022) reviewed nano-additives in geopolymer concrete and confirmed that nano-modification improves compressive strength, reduces porosity, and enhances resistance to chloride penetration and chemical attack (Gupta et al., 2022).

Microstructural studies also support these findings. Ahmed et al. (2022) conducted detailed microscopic investigations of alternative precursor geopolymers and reported that improved gel structure and reduced void connectivity significantly contribute to enhanced performance (Ahmed et al., 2022).

Zeolite-based geopolymer systems have also gained attention due to their porous aluminosilicate framework, which supports geopolymerization and contributes to improved adsorption and durability characteristics. Liu et al. (2020) reported that zeolite incorporation can improve binder stability and influence pore refinement in geopolymer matrices (Liu et al., 2020).

2.3.3 Bio-Based Geopolymer Composites

Bio-based geopolymer composites represent a major sustainable innovation in advanced geopolymer development. Agricultural waste ashes such as rice husk ash (RHA), sugarcane bagasse ash (SCBA), and other biomass residues have been investigated as silica-rich supplementary materials. Rashad (2018) reviewed the use of rice husk ash in geopolymer concretes and reported that RHA contributes to improved strength and durability due to its high amorphous silica content (Rashad, 2018).

Similarly, Ghosh et al. (2020) found that sugarcane bagasse ash can serve as an effective geopolymer precursor or supplementary material, contributing to sustainability while improving binder properties (Ghosh et al., 2020). Herki (2017) also emphasized that agricultural wastes offer an environmentally friendly precursor option for low-carbon geopolymer development, especially in developing countries where such wastes are abundant (Herki, 2017).

In addition, combining multiple agricultural ashes has shown promising results. Borthakur et al. (2021) reported that combined rice husk ash and bagasse ash systems improve geopolymer binder reactivity and produce enhanced mechanical properties compared to single-waste systems (Borthakur et al., 2021).

2.3.4 Carbon-Negative and Waste-Derived Geopolymers

Recent research has focused on carbon-negative geopolymer systems by incorporating waste-derived precursors and reducing activator environmental burden. Red mud, a hazardous waste from alumina industries, has emerged as a promising geopolymer precursor. Singhal et al. (2019) reviewed red mud-based geopolymer concrete and concluded that red mud contributes to sustainable waste utilization while providing acceptable strength and durability properties when blended with other aluminosilicates (Singhal et al., 2019).

Other industrial wastes such as cenospheres and calcium carbide waste have also been explored. Chen et al. (2020) reported that cenospheres contribute to lightweight and low-carbon geopolymer composites while improving thermal insulation performance (Chen et al., 2020). Uba et al. (2025) found that calcium carbide waste can enhance geopolymer concrete performance by improving binder reactivity and promoting sustainable waste reuse (Uba et al., 2025).

Volcanic ash is another naturally occurring precursor that supports low-carbon geopolymer systems. Hussain et al. (2018) demonstrated that volcanic ash-based alkali activated materials exhibit good binder properties and can serve as sustainable alternatives where industrial by-products are unavailable (Hussain et al., 2018).

Recycled waste materials such as glass waste and recycled aggregates are also being integrated into geopolymer concrete systems to improve circular economy performance. Pandey et al. (2023) reported that recycled glass waste enhances sustainability and contributes reactive silica for geopolymerization (Pandey et al., 2023). Similarly, Chaubey and Upadhyay (2021) confirmed that geopolymer concrete with recycled aggregates can achieve acceptable strength while reducing environmental impacts (Chaubey & Upadhyay, 2021).

Furthermore, mineral admixtures and precursor optimization continue to play a crucial role in achieving consistent high performance. Tang et al. (2021) highlighted that mineral admixtures improve durability and mechanical properties by refining pore structure and enhancing gel formation (Tang et al., 2021).

III. EVOLUTION OF MATERIALS IN LOW-CARBON GEOPOLYMER CONCRETE

The development of low-carbon geopolymer concrete (GPC) is strongly dependent on the evolution of its constituent materials. Unlike OPC-based systems, geopolymer binders rely on aluminosilicate precursors activated by alkaline solutions to form hardened polymeric networks. Over time, research has expanded from traditional industrial by-products such as fly ash and slag to alternative natural and waste-derived precursors, sustainable additives, and eco-friendly activators. This shift supports circular economy goals, reduces embodied carbon, and improves mechanical and durability performance.

3.1 Aluminosilicate Precursors

3.1.1 Fly Ash

Fly ash remains the most widely used precursor in geopolymer concrete due to its high silica and alumina content and its availability as a by-product of coal-fired power plants. Fly ash-based geopolymers offer significant carbon reduction potential by utilizing waste materials and reducing clinker-based cement consumption. However, fly ash systems often require heat curing for sufficient early strength, particularly when low-calcium fly ash is used.

High-calcium fly ash has been reported to improve geopolymer reactivity, early strength development, and setting behavior due to the formation of calcium-based hydration products. Sakai et al. (2015) confirmed that calcium-rich fly ash contributes to improved strength gain but may also influence microstructure and long-term stability (Sakai et al., 2015). Additionally, Shi et al. (2020) reported that high-volume fly ash geopolymer concretes can achieve low-carbon performance while maintaining acceptable strength, though mixture optimization remains essential (Shi et al., 2020).

3.1.2 Ground Granulated Blast Furnace Slag (GGBS)

GGBS is a key calcium-rich precursor that has significantly enhanced the evolution of ambient-cured geopolymer systems. The presence of calcium accelerates geopolymerization reactions and supports the formation of C-A-S-H type gels, which improves early compressive strength and reduces curing dependency. Kumar et al. (2017) emphasized that slag-based geopolymer systems demonstrate superior early-age strength and improved durability compared to fly ash-only binders (Kumar et al., 2017).

The combined use of fly ash and slag has been extensively investigated, and the ratio between these materials strongly influences mechanical performance. Anuradha et al. (2021) demonstrated that increasing slag content generally improves early compressive strength and enhances binder densification (Anuradha et al., 2021). Therefore, slag incorporation represents a major milestone in geopolymer material evolution, enabling wider field implementation.

3.1.3 Metakaolin

Metakaolin is a highly reactive aluminosilicate precursor derived from calcined kaolin clay. It is considered one of the most consistent and high-performance geopolymer raw materials due to its controlled mineralogical composition. Zhang and Fang (2017) reported that metakaolin-based geopolymer binders provide excellent compressive strength, refined microstructure, and improved durability, making them suitable for structural applications (Zhang & Fang, 2017).

However, metakaolin-based systems are often limited by higher cost compared to industrial by-products. Recent studies emphasize blending metakaolin with low-cost wastes or by-products to improve economic feasibility.

3.1.4 Rice Husk Ash (RHA)

Rice husk ash is an agricultural waste rich in amorphous silica and is increasingly explored as a sustainable geopolymer precursor or supplementary material. Rashad (2018) reviewed RHA geopolymer systems and found that the high silica content improves geopolymer gel formation, enhances compressive strength, and contributes to durability improvements by reducing pore connectivity (Rashad, 2018).

The combined use of rice husk ash with other agricultural wastes has also gained attention. Borthakur et al. (2021) reported that blending rice husk ash with bagasse ash results in improved geopolymerization efficiency and enhanced mechanical performance due to the complementary chemical composition of both ashes (Borthakur et al., 2021).

3.1.5 Red Mud

Red mud is a hazardous industrial waste generated from alumina production, containing alumina, silica, iron oxides, and alkaline residues. Its utilization in geopolymer concrete provides dual environmental benefits: reducing landfill disposal and producing low-carbon binder systems. Singhal et al. (2019) reported that red mud-based geopolymer concrete can achieve acceptable compressive strength and durability when blended with fly ash or slag to balance chemical composition (Singhal et al., 2019).

However, due to its high alkalinity and variable composition, red mud requires careful mix proportioning and pre-treatment for consistent performance.

3.1.6 Laterite Soil

Laterite soil is a naturally available aluminosilicate material rich in iron oxides, silica, and alumina. Its application in geopolymer concrete is emerging due to its widespread availability in tropical regions and its potential for low-cost sustainable construction. Laterite-based geopolymer systems are particularly relevant for rural and low-carbon infrastructure development.

Although limited studies exist compared to fly ash or slag, laterite soil offers promising potential as a local precursor, reducing dependency on industrial by-products and decreasing transportation-related emissions. Microstructural investigations of alternative precursors highlight that natural soil-based geopolymer binders can form stable aluminosilicate gel networks when properly activated (Ahmed et al., 2022).

3.1.7 Mine Tailings

Mine tailings are waste residues from mineral processing industries and represent an abundant source of silica and alumina-rich materials. Their use in geopolymer concrete contributes to sustainable waste management and supports the circular economy. Sen et al. (2018) highlighted that alkali activation of mine tailings can generate geopolymer binders with acceptable mechanical properties, although pre-treatment and particle size optimization are often required (Sen et al., 2018).

The use of mine tailings also faces challenges related to chemical variability and potential heavy metal leaching, requiring proper environmental evaluation.

Table 1: Major aluminosilicate precursors used in geopolymer concrete

Precursor	Typical chemical characteristics	Main gel/product	Major advantage	Major limitation
Fly ash	$SiO_2 + Al_2O_3 + Fe_2O_3$; Ca varies	N-A-S-H / C-A-S-H depending on Ca	Industrial by-product, low cost	Variable quality and reactivity
GGBS	High CaO, SiO_2, Al_2O_3	C-(A)-S-H	High early strength, ambient curing	Higher embodied emissions than some waste precursors
Metakaolin	High reactive $SiO_2 + Al_2O_3$	N-A-S-H	High reactivity and controlled composition	Requires calcination
Rice husk ash	High amorphous SiO_2	Si-rich aluminosilicate gel	Agricultural-waste utilization	High carbon if poorly burned
Sugarcane bagasse ash	SiO_2 with variable Al/Ca/K	Aluminosilicate/calcium-containing gels	Abundant agricultural residue	Variable composition
Waste glass powder	Predominantly amorphous SiO_2	Si-rich geopolymer gel	Waste-glass valorization	Low Al content; often needs Al-rich precursor
Red mud	Fe_2O_3, Al_2O_3, SiO_2, Na compounds	Mixed aluminosilicate/calcium gels	Industrial waste utilization	High alkalinity and impurities
Zeolite	Reactive aluminosilicate framework	N-A-S-H-type products	Natural mineral, high Si/Al reactivity	Resource variability
Mine tailings	Highly variable SiO_2, Al_2O_3, CaO, Fe_2O_3	Depends on mineralogy	Large-volume waste resource	Often requires activation/pre-treatment

3.2 Sustainable Additives in Low-Carbon GPC

3.2.1 Biochar

Biochar is a carbon-rich material produced from biomass pyrolysis and has recently gained attention as a sustainable additive in geopolymer concrete. Biochar enhances sustainability by acting as a carbon-sequestering material, potentially contributing to carbon-negative construction. Additionally, biochar can influence internal curing, pore refinement, and crack resistance due to its porous structure.

Agricultural waste-derived geopolymer systems have been widely promoted as sustainable solutions. Herki (2017) highlighted that biomass waste-based additives can enhance the sustainability and circular economy potential of geopolymer materials (Herki, 2017). The incorporation of biochar is particularly promising in low-carbon geopolymer concrete due to its ability to reduce density and improve thermal insulation.

3.2.2 Zeolite

Zeolite is a crystalline aluminosilicate mineral known for its high surface area and ion exchange capacity. Zeolite-based geopolymer systems have gained significant interest due to their ability to improve pore structure refinement and enhance durability. Liu et al. (2020) reported that zeolite incorporation can improve geopolymer stability and microstructural densification, thereby enhancing long-term durability performance (Liu et al., 2020).

Zeolite also contributes to improved adsorption properties, making it suitable for applications requiring chemical resistance and environmental remediation potential.

3.2.3 Nano Silica

Nano-silica has emerged as one of the most effective nano-additives for enhancing geopolymer concrete performance. Due to its high reactivity and extremely fine particle size, nano-silica acts as a nucleation site for gel formation and significantly refines the pore structure. Gupta et al. (2022) reviewed nano-additives in geopolymer concrete and concluded that nano-silica improves compressive strength, reduces permeability, and enhances durability against chloride and sulfate attack (Gupta et al., 2022).

Nano-silica also improves interfacial transition zones (ITZ) between aggregates and geopolymer binder, contributing to better mechanical performance.

3.2.4 Graphene Oxide

Graphene oxide is an advanced nano-material that enhances geopolymer concrete through crack bridging mechanisms, improved microstructural densification, and increased tensile performance. Though still limited in practical adoption due to cost, graphene oxide has shown significant potential for developing high-performance geopolymer composites.

Microstructural investigations have confirmed that nano-modified geopolymer systems demonstrate reduced microcrack formation and improved gel bonding compared to conventional mixtures (Ahmed et al., 2022).

3.2.5 Fibers

Fiber reinforcement is widely adopted to overcome geopolymer concrete brittleness and improve tensile and flexural strength. Various fibers such as steel fibers, polypropylene fibers, basalt fibers, and natural fibers have been used. Fiber-reinforced geopolymer concretes exhibit improved crack resistance, ductility, and post-cracking performance.

Mineral admixture studies show that fiber addition combined with optimized binder composition can significantly improve durability and mechanical behavior (Tang et al., 2021). This makes fiber reinforcement a crucial material advancement in low-carbon geopolymer concrete.

Table 2: Sustainable additives in low-carbon geopolymer concrete

Additive	**Typical reported dosage***	**Main function**	**Reported effect on strength**	**Main sustainability relevance**
Biochar	~1–15%	Filler, pore modifier, carbon storage, functional additive	5% biochar: **79.6 → 85.6 MPa (+7.5%)** in one GPC study	Biomass waste utilization + potential carbon storage
Zeolite	~5–30%	Reactive aluminosilicate, pore refinement	Performance depends strongly on activation and replacement level	Natural/mineral precursor; can reduce dependence on conventional precursors
Nano-silica	~1–4%	Nucleation, pore refinement, reactive SiO_2	One study: **25 → 35 MPa (+40%) at 4%**	Small dosage can produce microstructural enhancement
Graphene oxide	~0.02–0.10 wt%	Nano-reinforcement, crack control, conductivity	At **0.08 wt%**: compressive **+24.8%**, tensile **+37.7%**, flexural **+80.6%**, toughness **+105%**	Multifunctional/self-sensing potential
Fibres	~0.5–3% commonly investigated	Crack bridging, tensile/flexural reinforcement	Strongly dependent on fibre type, length and dosage	Renewable/waste fibres can replace conventional synthetic reinforcement

3.3 Eco-Friendly Activators

The environmental impact of geopolymer concrete is strongly influenced by the alkaline activator system. Traditional activators such as sodium hydroxide and sodium silicate contribute to embodied energy and carbon emissions. Therefore, modern research focuses on alternative low-carbon activators.

3.3.1 Sodium Carbonate Activators

Sodium carbonate is considered a safer and more eco-friendly alternative activator compared to sodium hydroxide. It offers reduced corrosiveness, easier handling, and lower environmental impact. Sodium carbonate activation may require longer curing time but can still provide stable strength development, particularly in slag-rich systems.

3.3.2 Waste-Derived Alkalis

Waste-derived alkaline activators represent an emerging sustainable approach for reducing the carbon footprint of geopolymer binders. Industrial by-products such as calcium carbide waste, waste glass-derived alkalis, and ash-derived alkaline solutions are increasingly explored. Uba et al. (2025) reported that calcium carbide waste enhances geopolymer concrete reactivity and contributes to improved strength performance, while also supporting sustainable waste management (Uba et al., 2025).

Similarly, Pandey et al. (2023) highlighted that recycled glass waste can act as a silica-rich contributor and may support activator development, improving geopolymer sustainability (Pandey et al., 2023). Chen et al. (2021) also emphasized that industrial by-products can enhance geopolymer performance while contributing to eco-friendly activator systems (Chen et al., 2021).

3.3.3 One-Part Activators

One-part geopolymer systems are an advanced development aimed at improving practical application. These systems use dry activator powders blended with precursors, requiring only the addition of water at the construction site. This approach reduces safety hazards associated with handling corrosive liquid alkaline solutions.

Tang et al. (2022) emphasized that calcined clay-based alkali activated materials support one-part geopolymer development due to consistent precursor reactivity (Tang et al., 2022). However, challenges remain in optimizing dry activator dosage and ensuring consistent performance.

Table 3: Eco-friendly activator systems reported in the literature

Activator category	**Activator / system**	**Reported dosage or ratio**	**Precursor**	**Curing**	**Reported compressive strength**	**Important observation**
Sodium carbonate	Na_2SiO_3 + Na_2CO_3	AA/FA = 0.15, 0.20, 0.25; Na_2SiO_3/Na_2CO_3 = 1:1	Fly ash	28 d	78.23 MPa at AA/FA = 0.20	Partial replacement of sodium silicate with Na_2CO_3 reduced setting time and porosity. (ResearchGate)
Sodium carbonate	Solid Na_2CO_3	Used as solid activator	Fly ash-based OPG	—	Up to 78.23 MPa reported in the reviewed study	Demonstrates feasibility of carbonate activation in one-part systems. (Wiley Online Library)
Waste glass-derived alkali	Waste glass + NaOH	30 g glass / 100 mL 10 M NaOH	Alkali-activated binder	28 d	28 MPa	Waste glass supplied soluble silica and enabled production of sodium-silicate-type activator. (ScienceDirect)
Waste glass-derived activator	Waste glass + NaOH	NaOH 10 M + 10–25 g glass/100 mL	Fly ash	7 d	14–36 MPa depending on glass dosage	Waste glass can provide silica while reducing dependence on commercial sodium silicate. (American Chemical Society Publications)
Waste glass-derived sodium silicate	Thermochemically synthesized glass activator	SiO_2/Na_2O modulus 0.5, 1.0, 1.5	Spent oil-filtering earth AAM	—	Study-specific	Demonstrates controlled production of solid sodium silicate from waste glass. (Springer)
One-part activator	Anhydrous Na_2SiO_3	Solid activator	FA/GGBFS systems	Various	Study-dependent	One-part system: dry precursor + solid activator + water. (ScienceDirect)
One-part activator	Solid NaOH	Solid dosage varies by study	FA/GGBFS	Various	Study-dependent	Eliminates handling of concentrated NaOH solution but remains highly caustic. (DOI)
One-part activator	Na_2CO_3	Solid activator	Fly ash	Various	78.23 MPa reported for Na_2SiO_3–Na_2CO_3 system	Lower handling complexity; carbonate activation is particularly relevant to solid/one-part systems. (Wiley Online Library)
One-part activator	Na_2SiO_3 + Na_2CO_3	AA/FA 0.20	Fly ash	28 d	78.23 MPa	Strong example for your review's quantitative comparison. (ResearchGate)

3.4 Emerging Trends and Material Optimization

The evolution of materials in low-carbon geopolymer concrete has shifted towards multi-source precursor blending and optimization strategies. Li et al. (2021) emphasized that optimizing precursor ratios is essential for achieving consistent strength and durability, especially under ambient curing conditions (Li et al., 2021). Precursor variability continues to be a major concern, as source-dependent chemical composition affects geopolymerization kinetics and microstructural stability. Yin et al. (2020) reported that variability in precursor sources leads to differences in reaction mechanisms, affecting long-term performance and durability (Yin et al., 2020).

Furthermore, low-carbon geopolymer development increasingly includes recycled aggregates, lightweight fillers such as cenospheres, and alternative industrial wastes. Chen et al. (2020) reported that cenospheres improve lightweight geopolymer performance and contribute to thermal insulation properties (Chen et al., 2020). Chaubey and Upadhyay (2021) confirmed that recycled aggregates can be effectively utilized in geopolymer concrete while maintaining acceptable strength performance and sustainability benefits (Chaubey & Upadhyay, 2021).

Natural precursors such as volcanic ash also support low-carbon geopolymer technology, particularly in regions where fly ash and slag availability is declining. Hussain et al. (2018) concluded that volcanic ash-based alkali activated materials can provide stable binder performance with reduced environmental impacts (Hussain et al., 2018)

IV. Emerging Trends and Future Directions in Low-carbon Geopolymer Concrete

The rapid advancement of low-carbon geopolymer concrete (GPC) has shifted research focus from basic material development toward intelligent, multifunctional, and sustainable construction systems. Emerging trends in artificial intelligence, nanotechnology, digital construction, circular economy integration, and smart infrastructure are shaping the next generation of geopolymer materials. These innovations aim to improve performance, scalability, economic feasibility, and environmental sustainability while supporting global net-zero construction goals.

4.1 Artificial Intelligence and Digitalization in Geopolymer Concrete

Artificial intelligence (AI) has become an important tool for optimizing geopolymer concrete mix design, predicting material performance, and reducing experimental costs. Traditional trial-and-error approaches are increasingly being replaced by machine learning algorithms capable of analyzing complex relationships among precursor materials, activator concentrations, curing conditions, and mechanical properties.

Garcia-Soriano et al. (2023) highlighted the growing role of AI in low-carbon concrete design, where predictive models assist in selecting sustainable material combinations with minimal carbon emissions. Similarly, Zhang et al. (2024) demonstrated that AI-based prediction models can accurately estimate compressive strength, durability, and workability of geopolymer concrete under varying mix conditions.

Digital technologies are also transforming construction planning and lifecycle management. Kim et al. (2023) reported that digital tools integrated with Building Information Modeling (BIM) and carbon assessment platforms help optimize net-zero construction planning. These systems support sustainable decision-making by evaluating embodied carbon, energy consumption, and long-term environmental impacts during the design stage.

Furthermore, Wang et al. (2022) introduced the concept of digital twin technology for geopolymer concrete infrastructure. Digital twins enable real-time monitoring, predictive maintenance, and structural health assessment throughout the service life of concrete assets. Such technologies are expected to improve infrastructure resilience, maintenance efficiency, and lifecycle sustainability.

AI-enabled energy optimization methods have also been explored for geopolymer production processes. Zhu et al. (2023) demonstrated that intelligent energy management systems can significantly reduce manufacturing energy consumption and optimize curing conditions for low-carbon geopolymer production.

4.2 Nanotechnology and Advanced Functional Materials

Nanotechnology has emerged as a transformative approach for enhancing the mechanical, thermal, and durability properties of geopolymer concrete. Nanomaterials improve geopolymer reaction kinetics, pore refinement, and interfacial bonding at the microstructural level.

Liu et al. (2021) emphasized that nanotechnology-enabled geopolymers exhibit superior compressive strength, reduced permeability, and enhanced resistance to chemical attack. Nano silica, graphene oxide, carbon nanotubes, and nano clay are among the most commonly investigated nanomaterials for geopolymer enhancement.

Graphene oxide and nano silica improve matrix densification and crack resistance, while carbon-based nanomaterials contribute to electrical conductivity and multifunctional sensing capabilities. Das et al. (2022) reported the development of ultra-high-performance multifunctional geopolymer composites with improved mechanical properties, self-sensing behavior, and durability performance.

Recent studies have also explored geopolymer nanocomposites for thermal energy storage applications. Nguyen et al. (2021) demonstrated that geopolymer-based nanocomposites can effectively store and release thermal energy, making them suitable for energy-efficient buildings and sustainable thermal management systems.

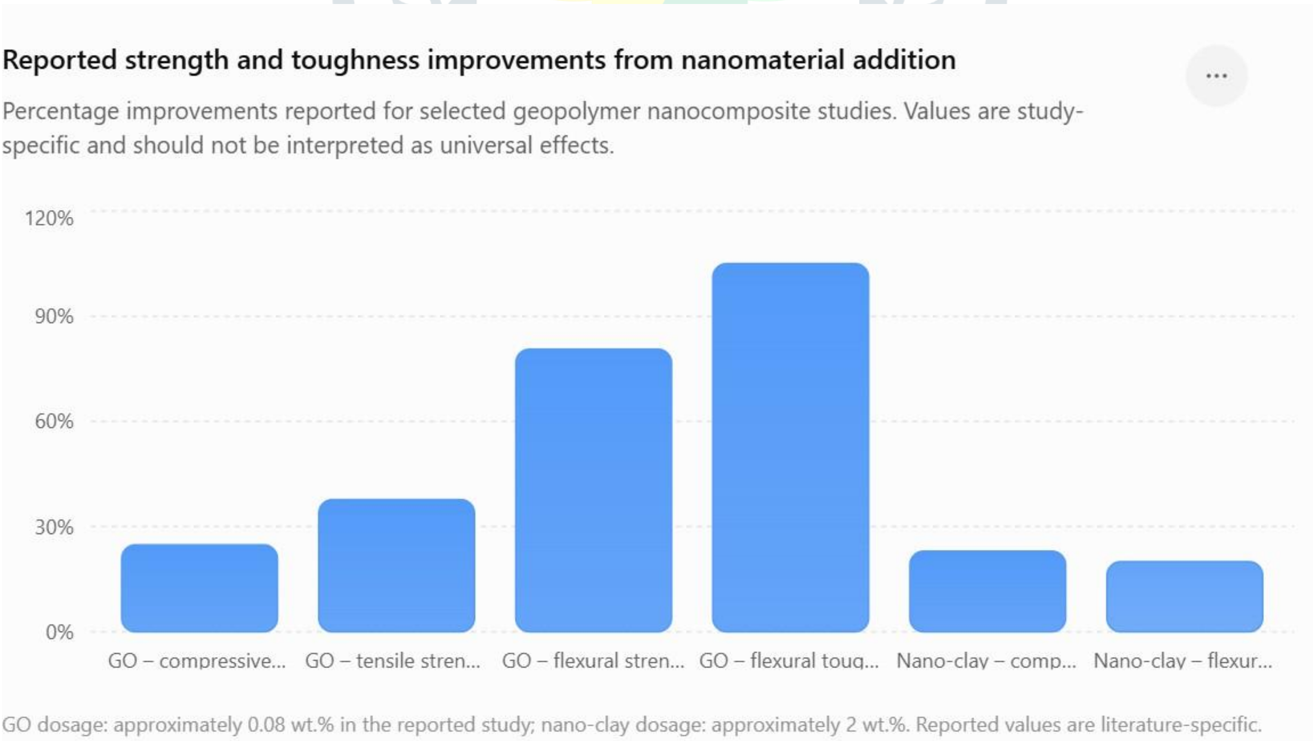

Fig. 1: Reported strength and toughness improvements from nanomaterial addition in geopolymer composites

Table 4: Quantitative comparison of nanomaterials in geopolymer composites

Nanomaterial	Reported dosage	Reported quantitative effect	Main mechanism	Major limitation
Nano-silica	~6 wt.%*	Improved strength and microstructure	Nano-filling + reactive silica	Agglomeration, water demand
Graphene oxide	~0.08 wt.%*	+24.8% compressive strength	Matrix densification + crack restriction	Dispersion
Graphene oxide	~0.08 wt.%*	+37.7% tensile strength	Crack bridging/load transfer	Cost
Graphene oxide	~0.08 wt.%*	+80.6% flexural strength	Nano-reinforcement	Agglomeration
Graphene oxide	~0.08 wt.%*	+105% flexural toughness	Crack bridging	Dispersion
Nano-clay	~2 wt.%*	+23% compressive strength	Pore refinement/filler effect	Workability
Nano-clay	~2 wt.%*	+20% flexural strength	Matrix densification	Agglomeration
Nano-alumina	~2 wt.%*	Improved mechanical properties	Filler + microstructural modification	Cost/workability
CNT	~0.25%	Electrical-property optimization	Conductive network	High cost/dispersion
Carbon black	~0.40%	Electrical-property optimization	Conductive network	Agglomeration

4.3 3D Printing and Additive Manufacturing

Additive manufacturing is one of the fastest-growing applications of geopolymer technology. Geopolymer materials are particularly suitable for 3D printing due to their rapid setting behaviour, reduced shrinkage, and low environmental impact.

Yin et al. (2022) reported significant advancements in geopolymer ink development for extrusion-based 3D printing systems. Optimized rheological properties, buildability, and interlayer bonding are essential for successful geopolymer printing applications. Nano additives, fibres, and viscosity modifiers are often incorporated to improve print quality and structural stability.

3D-printed geopolymer structures offer several advantages, including reduced construction waste, lower labour requirements, rapid construction speed, and design flexibility. One-part geopolymer systems further simplify the printing process by eliminating the handling of liquid alkaline activators.

The integration of AI with additive manufacturing is expected to improve automated quality control, process optimization, and real-time monitoring of printed geopolymer structures.

4.4 Ambient-Cured and High-Performance Geopolymers

One of the major challenges in geopolymer technology has been the requirement for elevated-temperature curing. Recent research has focused on developing ambient-cured geopolymer systems suitable for practical field applications.

Nguyen et al. (2024) developed high-performance ambient-cured alkali-activated materials capable of achieving excellent strength and durability under normal curing conditions. The incorporation of GGBS, nano silica, and optimized activator systems has significantly improved ambient geopolymer performance.

Hybrid geopolymer systems combining industrial by-products and natural aluminosilicate materials are also gaining attention for producing durable, low-carbon construction materials with reduced curing energy requirements.

Thermodynamic modeling of activator solutions has become an important research area for understanding geopolymer reaction mechanisms. Skane et al. (2025) highlighted the importance of thermodynamic simulations in optimizing activator chemistry, predicting phase formation, and improving geopolymer stability.

4.5 Smart and Multifunctional Geopolymer Systems

The development of smart geopolymer materials capable of self-monitoring and multifunctional performance is an emerging research direction. Xu et al. (2020) investigated smart sensing materials integrated into geopolymer concrete for monitoring durability, crack formation, moisture movement, and structural degradation.

Conductive additives such as graphene oxide, carbon fibers, and nano carbon materials enable self-sensing capabilities in geopolymer composites. These smart materials can provide real-time structural health monitoring without requiring external sensing devices.

Hybrid fiber reinforcement systems also contribute to multifunctional behavior. Singh et al. (2020) demonstrated that hybrid fiber-reinforced geopolymer concrete exhibits enhanced tensile strength, ductility, impact resistance, and crack control, making it suitable for structural and seismic applications.

4.6 Circular Economy and Sustainable Resource Utilization

The circular economy concept has become central to future geopolymer research and development. Geopolymer technology supports circular construction practices by converting industrial wastes, mining residues, and agricultural by-products into valuable construction materials.

Gupta et al. (2020) proposed a circular economy framework for sustainable construction materials, emphasizing resource efficiency, waste minimization, and carbon reduction. Biomass ash-based geopolymers investigated by Pereira et al. (2019) further demonstrated the potential of agricultural waste valorization in low-carbon construction.

The use of waste-derived alkalis, recycled aggregates, mine tailings, and biochar aligns geopolymer technology with global sustainability goals and zero-waste strategies.

4.7 Economic and Policy Perspectives

Although geopolymer concrete offers significant environmental advantages, large-scale implementation still faces economic and policy-related challenges. Chandra et al. (2023) analyzed the geopolymer concrete market and identified barriers related to material standardization, supply chain limitations, lack of design codes, and industry awareness.

Life-cycle cost analysis has shown that geopolymer infrastructure can provide long-term economic benefits despite higher initial processing costs. Yao et al. (2021) reported that improved durability and lower maintenance requirements contribute to reduced overall lifecycle costs.

Sociotechnical barriers also influence adoption rates. Lu et al. (2020) emphasized that industry acceptance, government regulations, technical expertise, and stakeholder awareness play crucial roles in accelerating low-carbon construction adoption.

4.8 Climate Resilience and Infrastructure Applications

Future geopolymer systems are increasingly being designed for resilience under extreme environmental conditions. Rahman et al. (2021) investigated geopolymer concrete performance under severe climatic conditions, including high temperature, freeze–thaw exposure, and aggressive chemical environments.

Mass concrete applications have also gained attention because geopolymer binders generate lower heat of hydration compared with OPC systems. Gong et al. (2019) reported that geopolymer concrete significantly reduces thermal cracking risks in large infrastructure elements such as dams, bridge foundations, and retaining structures.

Multi-scale modeling approaches proposed by Costa et al. (2020) further improve understanding of geopolymer behavior from nano-scale gel formation to macro-scale structural performance.

4.9 Future Research Directions

Future research in low-carbon geopolymer concrete is expected to focus on:

- Development of carbon-neutral and waste-derived alkaline activators
- AI-assisted autonomous mix design and optimization
- Large-scale field implementation and performance validation
- Standardization of geopolymer mix design procedures and design codes
- Multifunctional smart geopolymer systems with sensing capabilities
- Integration of geopolymer technology with digital construction and robotic manufacturing
- Climate-resilient geopolymer infrastructure materials
- Circular economy-based resource management and industrial symbiosis

Overall, the future of geopolymer concrete lies in the integration of sustainability, digitalization, intelligent materials, and advanced manufacturing technologies to achieve durable, resilient, and carbon-neutral infrastructure systems.

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