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Research Paper

A Critical Review of Geopolymer Concrete: Mechanisms, Mix Design Methodologies, and Circular Economy Potentials

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Abstract: *Geopolymer concrete (GPC), recognised as a third-generation sustainable binder, presents a transformative alternative to ordinary Portland cement (OPC) by mitigating CO_2 emissions and valorising industrial/agricultural waste. This comprehensive review synthesizes the historical evolution, chemical mechanisms, mix design methodologies, and diverse applications of GPC. Formed through alkali activation of aluminosilicate precursors (e.g., fly ash, slag, metakaolin) below 100°C, GPC exhibits superior mechanical properties, exceptional durability in aggressive environments, and high thermal stability. Despite advances in mix design, which span target strength, performance-based, and statistical approaches, standardization remains a challenge due to precursor variability and curing dependencies. GPC's circular economy potential is demonstrated through global infrastructural applications (e.g., pavements, precast elements, wastewater treatment) and waste encapsulation. However, barriers such as efflorescence, high activator costs, and long-term data gaps hinder widespread adoption. Future research must prioritize scalable production, lifecycle assessment, and codification to unlock GPC's full potential as a cornerstone of sustainable construction.*

Keywords: *Geopolymer concrete; Alkali-activated materials; Sustainable construction; Circular economy; Mix design; Industrial waste valorization; and Durability.*

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I. Introduction

Geopolymer, considered the third-generation cement after lime and OPC (Singh et al., 2015), was named by Davidovits in the 1970s for amorphous mineral binders similar to zeolite (Davidovits, 1988). Derived from 'Geosynthesis', it forms artificial rock below 100°C, offering enhanced hardness, durability, and heat stability. Any material rich in amorphous Silica and Alumina is a potential source (Davidovits, 2002). Also known as inorganic polymer, alkali-activated cement, etc. (Rajamane et al., 2012), geopolymer avoids limestone calcination and high temperatures, reducing fuel use and greenhouse gases, making it an eco-friendly OPC substitute (Bondar, 2013). Chemically, it forms 3D (SiOAlO) polymer chains in a highly basic environment (Ma et al., 2018). As a green binder (Hamdane et al., 2021), it conserves energy, protects the environment, and utilizes industrial waste (Amran et al., 2020). GPC matches OPC's mechanical properties (Hassan et al., 2020) but offers superior characteristics and high stability in harsh conditions (Jiang et al., 2020).

GPC is a major research focus due to its sustainability, eco-friendliness, superior mechanics, and ability to use industrial/agricultural waste as precursors (Shehata et al., 2022; Jalal and Srivastava,2025). Fillers can enhance properties for specific applications (Çevik et al., 2018). GPC is an OPC alternative primarily due to lower CO2 emissions and performance benefits (Cong and Cheng, 2021; Parah et al.,2025a), enabling efficient waste management, reduced raw material use, and lower emissions (Yang et al., 2013). Using abundant industrial/agricultural waste makes it more cost-effective than OPC, which requires specific, expensive ingredients (Odeh et al., 2024). Unlike cement hydration, water is expelled during geopolymerisation curing/drying, reducing water needs and improving workability (Aleem and Arumairaj, 2012). Geopolymers require manufacturing below 100°C and emit six times less CO2 than cement (Duxson et al., 2007). Mild heat curing initiates polymerisation in GPC, unlike OPC (Suwan and Fan, 2014). GPC gains strength via polymerisation, OPC via hydration (Chandrakanth and Koniki, 2020; Abbasb and Majdi, 2017). Key differences are GPC's use of alkaline activators (Na_2SiO_3, NaOH) to activate precursors and the absence of OPC (Umer et al., 2024). GPC's high early strength and ambient curing reduce construction time versus OPC (Parathi et al., 2021).

Despite differences, GPC batching, mixing, and casting resemble OPC (Jalal et al., 2025). FA and GGBS, primary GPC ingredients, are now used in OPC blends (hybrid cement) (Liu et al., 2024). Adding activators to hybrid cements is also being researched (Turkoglu et al., 2023).

1. **Historical development of geopolymers:**

Alkali-activated materials (AAMs) are synthetic mineral products primarily composed of hydrous alkali and/or alkaline-earth metal aluminosilicates (Provis, 2018). Used as an alternative to Portland cement for over 120 years (Ponomar et al., 2023), initially due to cost and availability in Europe and the former Soviet Union (Van Deventer et al., 2010), their use expanded significantly in the last 30 years for reducing CO_2 emissions by 80–90% (Davidovits, 1993; Duxson et al., 2007).

The search for fire-resistant materials in the early 1940s led Ukrainian scientist Glukhovsky to discover alkali-activated alumino-silicates in the 1950s (Glukhovsky et al., 1957). Glukhovsky's team at Kyiv National University studied alkali-activation of soils and industrial wastes post-WWII, publishing *Soil Silicates* in 1952 on using sodium silicate with soils, sand, GGBS, and FA (Ponomar et al., 2023). Pozzolanic additives (finer silica/alumina-rich by-products) were heavily used since 1960 to achieve strengths of 50–90 MPa for demanding structures (Dinakar et al., 2008; Bumanis et al., 2020). From the 1960s, Glukhovsky's institute constructed various infrastructure using alkali-activated slag, demonstrating high durability and compact microstructure (Krivenko, 2017; Xu et al., 2008). Glukhovsky later identified key reaction products (calcium silicate hydrates, calcium/sodium alumino-silicate hydrates) in these materials, termed soil cement or alkali cement (Ponomar et al., 2023).

Following a 1970 fire in France, Davidovits sought non-flammable silicon-based materials (Davidovits, 1993). In 1972, he and Latapie created water-resistant ceramic tiles from kaolinitic clay and NaOH at 150°C (Davidovits, 2002a). That year, Davidovits synthesized a "geopolymer" (French: mineral polymers from geochemistry), a 3D silico-aluminate (Davidovits, 2017). Initial applications (1973-1976) included fire-resistant chipboard panels (Davidovits, 1972). Davidovits revived alkali-activated cement research in 1979 (George, 2010), coining the term "geopolymer" via the Commission of the European Communities for materials using rock-forming minerals (Davidovits, 1981). He founded the Institute of Geopolymer in 1979 (Srivastava and Gadhave, 2015). Early geopolymer research focused on metakaolin after discovering that alkalis accelerate GGBS setting (Davidovits, 1991). The first industrialized geopolymer, Pyrament, was developed in 1985 and launched in the US in 1986 (Davidovits and Sawyer, 1985).

Geopolymers gained significant civil engineering interest since the 1990s for their potential and low carbon footprint (Nagaraju et al., 2023). Research on geopolymer concrete was minimal before 2001 but increased dramatically after 2016 to assess its performance (Shehata et al., 2022).

2. **Mechanism and Chemistry of Geopolymerisation:**

Synthesis kinetics knowledge is crucial for developing and optimizing materials, as it regulates microstructure and final properties (Mittemeijer, 2010). In geopolymerization, alkaline activators and aluminosilicate sources are vital (Siyal et al., 2024). This process involves the rapid reaction of Si and Al minerals in alkali, forming a 3D polymeric structure of Si-O-Al-O bonds:

$$Mn\ [-(SiO_2)\ z\text{-}AlO_2]\ n.\ wH_2O \ldots\ldots\ldots\ldots\ldots \text{ Eqn (1)}$$

Where:

M = the alkaline element or monovalent cation such as potassium, sodium, or calcium

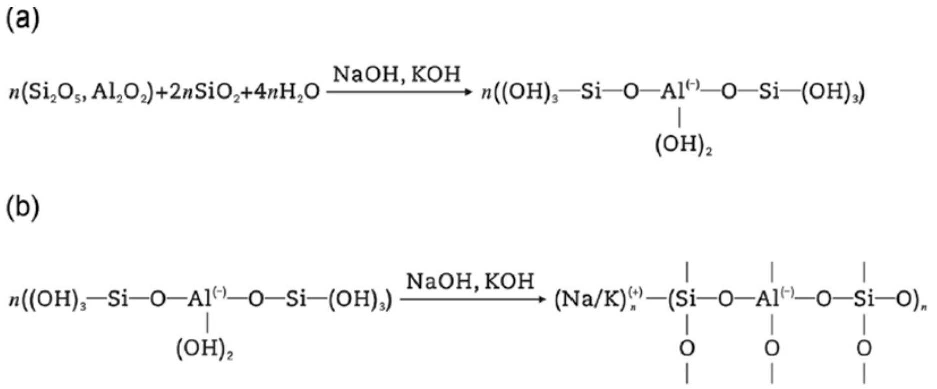
n = the degree of polycondensation or polymerisation

– = the symbol "- "indicates the presence of a bond

z = 1,2,3 or higher up to 32 (Van Chanh et al., 2008). Three varieties of silicon-aluminum (Gel 3, Si/Al = 1), silicon-aluminum (Gel 2, Si/Al = 2), and silicon-aluminum (Gel 1, Si/Al = 3) geopolymer structures are distinguished based on the Z value (Karthik and Mohan, 2021).

Geopolymers form aluminosilicate frameworks termed Polysialates. "Sialate" abbreviates alkali silicon-oxo-aluminate (alkali: Na, K, Li, Ca), and "poly(sialate)" denotes geopolymers containing ≥1 sialate unit (Abdullah et al., 2011). Structures include: Poly(sialate) (-Si-O-Al-O-), Poly(sialate-siloxo) (-Si-O-Al-O-Si-O-), and Poly(sialate-disiloxo) (-Si-O-Al-O-Si-O-Si-O-) (Davidovits, 1999). The network comprises SiO_4 and AlO_4 tetrahedra sharing oxygen atoms, charge-balanced by cations (Na^+, K^+, Ca^{2+}). Chains/rings form via sialate bridges, creating amorphous to semi-crystalline Polysialates (Van Deventer et al., 2007).

Equations used to depict the schematic creation of geopolymer material (a) and (b) (Zhang et al., 2018) are shown below.



$$n(\mathrm{Si_2O_5, Al_2O_2}) + 2n\mathrm{SiO_2} + 4n\mathrm{H_2O} \xrightarrow{\mathrm{NaOH, KOH}} n((\mathrm{OH})_3\text{—Si—O—}\underset{(\mathrm{OH})_2}{\mathrm{Al}^{(-)}}\text{—O—Si—}(\mathrm{OH})_3)$$

$$n((\mathrm{OH})_3\text{—Si—O—}\underset{(\mathrm{OH})_2}{\mathrm{Al}^{(-)}}\text{—O—Si—}(\mathrm{OH})_3) \xrightarrow{\mathrm{NaOH, KOH}} (\mathrm{Na/K})_n^{(+)}\text{—}(\underset{\mathrm{O}}{\mathrm{Si}}\text{—O—}\underset{\mathrm{O}}{\mathrm{Al}^{(-)}}\text{—O—}\underset{\mathrm{O}}{\mathrm{Si}}\text{—O})_n$$

Figure 1. Schematic representation of the formation of geopolymer materials (Zhang et al., 2018). (a) Geopolymer precursor. (b) Geopolymer backbone.

The exact mechanism for geopolymer setting and hardening, besides its reaction kinetics, remains unclear. The conceptual model, developed by Davidovits (1988) and modified by Shi et al. (2011), separates polycondensation into gelation and reconstitution phases, differing from Davidovits' model. Gelation involves dehydration, producing a regenerated oligomeric gel as aluminosilicate is absorbed. This dehydrated and condensed polymer gel ultimately forms the geopolymer's 3D network structure (Karthik and Mohan, 2021).

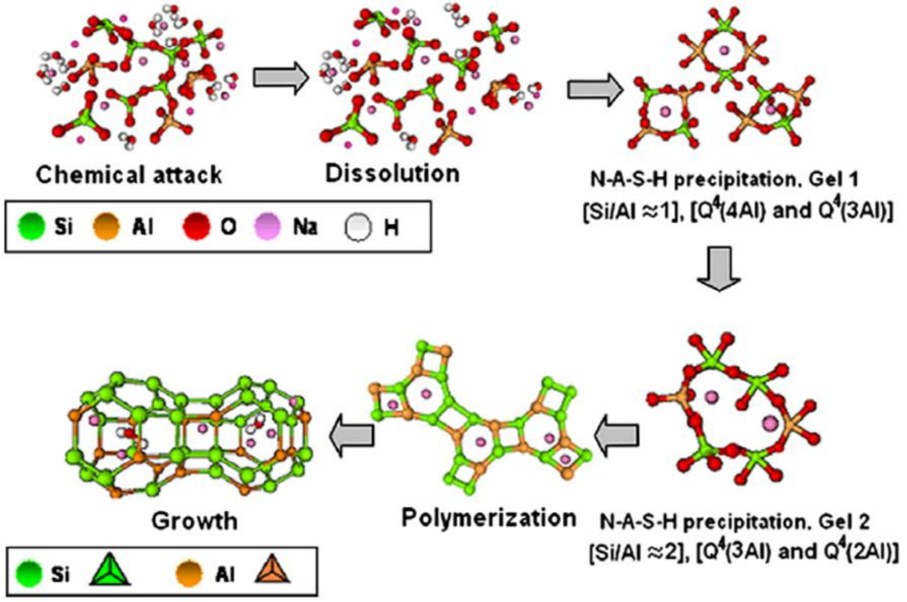


Figure 2. Conceptual model of geopolymerisation (Shi et al., 2011)

This model, developed by Davidovits (1988) and modified by Shi et al. (2011), consists of the following phases:

a) **Dissolution/Destruction:** Alkaline solution breaks covalent Al–O–Si and Si–O–Si bonds, forming a colloidal phase of Al–O and Si–O tetrahedral monomers.

b) **Diffusion/Equilibration:** Aluminosilicate dissolution continues; Si, Al, and aluminosilicate molecules reach equilibrium. Dissolved monomers diffuse, reducing surface Al/Si concentration.

c) **Transportation/Orientation/Condensation:** Dissolved ions form monomers. Rapid aluminosilicate breakdown causes neighbouring Si/Al molecules to react; OH^- ions form an O bond, releasing H_2O (trapped in pores). Reorganization continues, influenced by thermodynamics/kinetics, affecting physical properties.

d) **Polycondensation/Polymerisation:** Al–O/Si–O tetrahedra and Si/Al hydroxides polymerize into an amorphous 3D N-A-S-H gel network (Si–O–Al–O bonds).

e) **Setting/Hardening/Crystallization:** Dehydration and crystallization form a hardened, high-strength geopolymer. Gentle heat (~90°C) evaporates H_2O, creating discontinuous nanopores that enhance functionality. Water aids processing but doesn't participate chemically (unlike OPC hydration) (Hardjito et al., 2004). Crystallization involves bonding unaltered solids (Van Chanh et al., 2008).

However, these processes often overlap and occur nearly simultaneously, making independent analysis challenging (Palomo et al., 1999).

3. Preparation process of geopolymers

Geopolymers form at room or slightly elevated temperatures by dissolving alumino-silicate materials (e.g., kaolin, fly ash, blast furnace slag) in strong bases like NaOH or KOH (Davidovits, 1988; Karthik and Mohan, 2021). The products are amorphous to semi-crystalline with good/high mechanical properties (Davidovits, 1988).

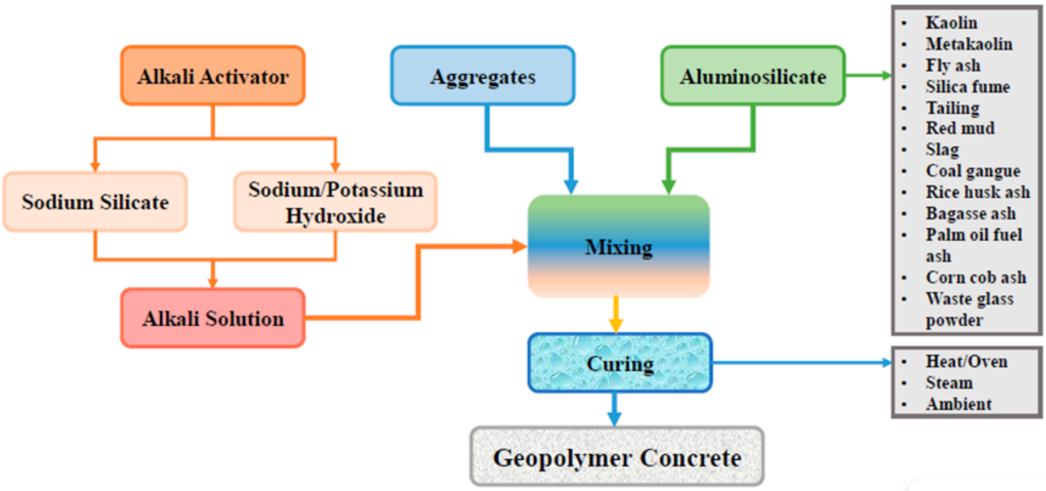


Figure 2. Schematic representation of the geopolymer production process (Yang et al., 2022)

The manufacture of geopolymer materials involves the following main techniques:

a) **Pouring method:** Similar to conventional concrete, requiring extra water (~20–40% mass) for fluidity (Shehata et al., 2022; Yadav et al., 2025).

b) **Compression moulding:** For precast work; mixes solids and activator into a slurry pressed at 5–10 MPa for high strength (~100 MPa) (Wang et al., 2005).

c) **Hot-pressing method:** Applies simultaneous heat and pressure for rapid production of high-strength, low-porosity matrices (Ranjbar et al., 2017).

d) **Microwave-assisted method:** Uses microwave irradiation for localized heating, enhancing dehydration to achieve optimal compressive strength (Sun et al., 2020).

e) **Ultrasonic-assisted method:** Ultrasonication enhances raw material dissolution, improves gel distribution/binding, and promotes semi-crystalline phases, increasing compressive strength and thermal stability (Feng et al., 2004).

4. Mix proportioning of GPC

Despite growing interest in GPC (Nguyen et al., 2020), the lack of a universal mix design method persists due to complex proportioning variables and multiple influencing factors (Matsimbe et al., 2022). Key variables include inconsistent raw materials, alkali activator type/dosage, and curing schemes (Li et al., 2018), limiting GPC's structural use despite superior properties over OPCC (Kanagaraj et al., 2023).

Early approaches beyond trial-and-error included Taguchi (Karthik and Mohan, 2021; Memis and Bilal, 2021), particle packing (Bondar et al., 2019), and response surface methodology (Mohammed et al., 2019; Shi et al., 2022), but these are material/condition-specific. Critical factors are AL/B ratio, alkali type/dose, SS/SH ratio, Ms, and curing (Ansari et al., 2023). Hardjito and Rangan (2005) found that only H2O-Na2O and water-geopolymer solids ratios inversely affected fly ash GPC strength (up to 64 MPa); other parameters had no influence. Recent studies show that higher curing temperatures and NaOH concentration yield optimal strength (Thapa et al., 2024), with 14M NaOH optimal for specific FA/palm shell GPC (Kupaei et al., 2013). Ukraine released the first slag-based GPC standard in 1984 (Ansari et al., 2023).

Current GPC mix design techniques, classified into target strength, performance-based, factorial model, and statistical methods, depend on the source materials.

4.1. Target Strength Approach:

Classified by fixity of water, binder, or paste content (Li et al., 2019), this method designs GPC for target strength and workability (Ansari et al., 2023). Key stages are defined below:

- **AL/B ratio:** Critical for strength/durability after NaOH concentration (Thunuguntla et al., 2018). Lower AL/B increases strength via higher binder (Rao and Kumar, 2020; Yadav et al., 2025a); higher AL/B reduces alkali concentration, increases porosity, and lowers strength (Zhang and Wang, 2015; Joseph and

Mathew, 2012). AL/B directly affects slump (Junaid et al., 2015). Optimizing S/B and SS/SH ratios yielded 104 MPa HSGPC (Gaurav et al., 2024).

- **Paste volume:** Comprises precursor, activator, and water. Affects slump (Thunuguntla and Rao, 2018), but 30–33% volume has minimal strength impact (Rafeet et al., 2017). Calculated by fixing water, binder, or paste content (Ansari et al., 2023). 200 kg/m³ alkaline liquid ensures workability (Reddy et al., 2018).
- **Binder content:** Determined by strength requirements. Higher strength (80 MPa) achieved with aggregate packing density (0.78) and binder content (0.33) (Ng and Foster, 2013).
- **Aggregates:** 70% total aggregate and FA/TA=0.35 recommended for target slump/strength (Joseph and Mathew, 2012).
- **FA/TA ratio:** Governs workability and durability (Jalal et al., 2025).
- **Admixtures:** Fine-tune properties for target strength (Jalal et al., 2025).
- **Proportion adjustment:** Trial batches refine mixtures to meet strength/durability standards.

4.2. Performance-Based Approach:

Chosen per production needs (Li et al., 2019), this lab-intensive method (Azimi-Pour et al., 2020) designs mixes based on durability (e.g., Cl^- penetration) (Ansari et al., 2023). Key factors include Na_2O%, SiO_2/Na_2O ratio (Ms), and W/B (Bondar et al., 2018).

Methods include:

- Close packing/excess paste theories + Taguchi optimization (Li et al., 2018).
- Absolute volume/particle packing for local materials, correlating strength (31–62 MPa) with AAS/B=0.4–0.8 (BJ and Parthasarathy, 2024).
- Limitations: Inadequate for marine GPC, as voids/sorptivity/28-day strength poorly predict chloride resistance (Noushini and Castel, 2018). Standards must shift from prescriptive to performance-based (van Deventer et al., 2015).

4.3. Factorial Model:

Uses statistical designs (e.g., fractional factorial, Taguchi) to optimize components for performance/sustainability (Selvakumar et al., 2024; Bj and Parthasarathy, 2024). Combines with GRA/RSM to enhance strength/workability (Ali et al., 2024; Driouich et al., 2023).

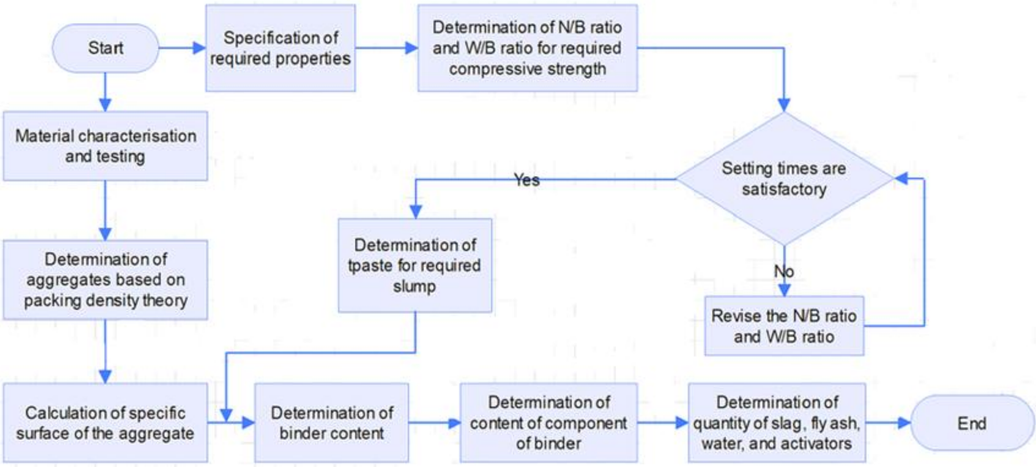


Figure 3. Performance-based mix design approach (Courtesy: Li et al., 2018, cited by Ansari et al, 2023)

4.4. Statistical Approaches:

Develop linear/non-linear strength predictions. Traditional models fail with diverse/new data due to fixed equations (Zhang et al., 2022a; Chaabene et al., 2020; Aneja et al., 2021). Methods include:

- **Taguchi:** Orthogonal arrays reduce trials. First used for 55 MPa GPC, testing aggregate, AL/FA, SS/SH, and curing (Olivia and Nikraz, 2012).
- **Multivariate regression model (MRM):** Models variable relationships (Binder, 1985; Su et al., 2011). Rarely applied.
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- **Multivariable polynomial regression model (MPRM):** Predicts setting time/slump/strength via AL/B, slag, Aw/B, and SS/SH. Strength ↑ with GGBS content (Hadi et al., 2019).
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- **Response surface methodology (RSM):** Optimizes factors via experiments/modeling (Box and Wilson, 1992). Reduces trials, enhances efficiency with target strength (Ansari et al., 2023; Upasani and Banga, 2004).
- **Artificial neural network approaches *(*ANN):** Predict hardened properties (e.g., strength) like human cognition (Akbarzadeh et al., 2016; Leiva-Villacorta and Vargas-Nordbeck, 2019; Dao et al., 2019).

5. Types of GPC

Geopolymer structure is categorized by Si/Al ratio: poly(sialate) (Si: Al=1), poly(sialate-siloxo) (Si: Al=2), poly(sialate-disiloxo) (Si: Al=3), and sialate link (Si: Al>3) (Taki et al., 2020). Geopolymer-zeolite composites, combining geopolymer and zeolite characteristics, can form (Rozek et al., 2019). GPC is classified by raw material quantity:

5.1. Unary GPC: Uses a single SCM binder (Aldred and Day, 2012; **Lloyd and Rangan, 2010a),** commonly FA or GGBS (Panda et al., 2020). It exhibits high compressive strength, often exceeding OPC (Davidovits, 1991). FA-GPC shows superior durability over OPC (Pasupathy et al., 2018), lower elastic modulus (5–28%), but higher compressive (55 MPa), tensile, and flexural strengths (Olivia and Nikraz, 2012). Metakaolin-GPC has higher strength properties but lower thermal conductivity than OPC (Marin-Lopez, 2009).

5.2. Binary GPC: Combines two SCMs (e.g., FA-slag, FA-RHA) for versatile properties (Nagajothi et al., 2022). FA-GGBS is common, being eco-friendly (Sherwani et al., 2020), with setting time decreasing and strength increasing with GGBS content (Lee and Lee, 2013; Nath and Sarkar, 2014). It offers excellent fire resistance (Aslani, 2016; Ren et al., 2016). FA-slag GPC deteriorates less than OPC in sulphate exposure, though more with magnesium sulphate (Bhutta et al., 2014; Valencia Saavedra et al., 2016). Other combinations include clay-FA and Aeolian pumice-metakaolin for lightweight GPC (Occhipinti et al., 2020).

5.3. Ternary GPC: Uses three SCMs to improve performance and durability (Kumar et al., 2021), though less explored than unary/binary (Huseien et al., 2023). Adding POFA to FA-GGBS improves properties like residual compressive strength and reduces water absorption (Huseien et al., 2023). Mix composition and curing temperature (>27±2°C) significantly impact reaction products and strength (Kubba et al., 2018; Hardjito et al., 2004), with ~60°C for 24h optimal (Nath and Sarker, 2014). Ternary GPC has higher mechanical strength and can be more economical than OPC (Choudhary et al., 2024).

5.4. Quaternary GPC: Uses four SCMs to optimize properties, but is insufficiently researched. Binary and ternary blends are commonly used to meet application demands.

6. Potential applications of geopolymer concrete based on their performance

Geopolymer concrete (GPC) offers high potential for trade applications due to its high-temperature resistance, superior sulphate/acid resistance, better abrasion resistance, low shrinkage, low thermal conductivity, rapid compressive strength gain (Torres-Carrasco and Puertas, 2017), enhanced durability, and economic benefits from using industrial/agricultural waste (Hassan et al., 2019). Its cost-effectiveness compared to OPC concrete is demonstrated (Assi et al., 2020; Davidovits, 1999), alongside a significant CO2 reduction (22–72%) even at equivalent cost (Degefu et al., 2022), though costs can vary based on logistics and energy (McLellan et al., 2011). Adoption rates vary globally (Zhang et al., 2014).

Australia showcases significant GPC use in infrastructure: water tanks, pavements, precast beams, bridge decks, and airport pavements (Aldred and Day, 2012). The University of Queensland's Global Change Institute features the world’s first cementless concrete building using GGBS/FA (Aldred and Day, 2012). Brisbane West Well Camp Airport utilized 70,000 tonnes of GPC (Parathi et al., 2021). South Africa employed FA-slag GPC for a slab achieving 51MPa (Matsimbe et al., 2022).

GPC improves indoor air quality, crucial as buildings contribute to ~90% of pollution exposure (Hoisington et al., 2019), reducing health risks from hazardous building materials (Petrovic, 2017) and promoting mental well-being (Hoisington et al., 2019). Eco-friendly materials like GPC mitigate diseases (Omer and Noguchi, 2020).

Global applications include:

- A 100 m double lane in India (Rungta, 2020)
- Precast box culverts in Australia (Rangan, 2014)
- A 6x4m retaining wall (Aldred and Day, 2012)
- Airport/road repairs (Ramani, 2014)
- Precast bridge decks in Australia (Aldred and Day, 2012)

GPC is ideal for highway repairs due to high strength and cost-effectiveness (Almutairi et al., 2021; Shehata et al., 2022), especially ternary blends (FA/GGBS/silica fume) (Dave et al., 2020; Tayeh et al., 2020), and is used in Thailand (Dave et al., 2020). It also produces tiles for harsh conditions (de Azevedo et al., 2021; Marvila et al., 2021).

Structurally, GPC is used for beams, columns, slabs, pavements, railway sleepers, and pipes (Parathi et al., 2021; Almutairi et al., 2021). Precast applications excel due to controlled curing, enabling sleepers and pipes (Almutairi et al., 2021), including high-resistance sleepers for Spanish railways (Shi et al., 2011). Prestressed GPC beams show higher crack resistance and lower stress loss than OPC (Neupane and Hadigheh, 2021). Its acid resistance benefits sewer pipes and rehabilitation (Almutairi et al., 2021; Shehata et al., 2022), as demonstrated in Houston (Matthews et al., 2015) and outperforms OPC pipes (Lloyd and Rangan, 2010). Alkali-activated coatings significantly reduce chloride-induced corrosion (Aguirre-Guerrero and de Gutiérrez, 2021).

Beyond construction, geopolymers are used in fire-resistant materials, ceramics, waste stabilization, water treatment adsorbents (Shikuku and Sylvain, 2019), and high-tech materials (Ferone et al., 2013), though handling limitations restrict broader use (Neupane, 2016). Their adsorption properties effectively remove water contaminants (Elgarahy et al., 2023) and manage industrial waste (Mehta and Siddique, 2016), exemplified by sealing toxic landfills in Germany (Davidovits, 2002) and encapsulating hazardous waste to protect groundwater (Davidovits, 2002; Shehata et al., 2022).

GPC is sustainable and cost-effective due to waste utilization, low CO2/energy, and early strength (Davidovits, 2002; Rangan, 2014). Momentum grows with novel precursors like mining waste (Rahman and Al-Ameri, 2021) and phosphate sludge (Dabbebi et al., 2018; Moukannaa et al., 2018; Wu et al., 2020), supporting "zero waste" goals (Zaman and Lehmann, 2013).

Despite its promise, GPC faces barriers: efflorescence risk (Babaee and Castel, 2024), activator aggressiveness, high curing temperatures, complex mix design, precursor supply issues, lack of long-term data, and the need for standardized databases (Sharmin et al., 2024; Van Deventer, 2017; Provis et al., 2019).

7. **Source materials for GPC**

Aluminosilicate source materials are essential for geopolymer synthesis. Utilizing natural/waste precursors and low-cost alkali hydroxides offers significant environmental benefits: conserving resources, recycling materials, reducing energy, limiting waste, and lowering emissions (Adewuyi, 2021; Xu and Shi, 2018; Rasaki et al., 2019).

Common source materials fall into four categories:

- Clays & clay minerals: e.g., kaolin, kaolinite, meta-kaolinite, calcined clay, zeolite (Adewuyi, 2021).
- Fly ash: e.g., coal fly ash, volcanic ash, ignition ash (Xu and Shi, 2018).
- Slag: e.g., furnace (iron) slag, granulated blast (steel) slag (Rasaki et al., 2019).
- Industrial wastes: e.g., mine tailings, ceramic waste, melt-quenched aluminosilicates, glass, mixtures (Falah and MacKenzie, 2020).

Geopolymer starting materials primarily contain Si, Al, and O, plus elements like K, Na, H, Ca, and Mg. Metakaolin and fly ash (FA) are frequently used. Kaolin, rich in kaolinite ($Al_2O_3{\cdot}2SiO_2{\cdot}2H_2O$), is abundant naturally (Maged et al., 2020). Metakaolin, produced by thermally decomposing kaolin above 550°C (dihydroxylation), undergoes significant structural rearrangement (Rozek et al., 2019). Fly ash is a fine, glassy powder by-product from coal combustion (Ren et al., 2021). Common activators are alkali hydroxides (KOH, NaOH) and/or alkali metal silicates (Na_2SiO_3, K_2SiO_3).

8. **Circular economy of geopolymers**

Global population growth, industrial activity, waste generation, resource scarcity, and high energy/goods demand drive the adoption of the circular economy (CE) (Elgarahy et al., 2022). CE creates value-added resources using techno-economic technologies without non-renewable resources, enhancing ecosystem carrying capacity (Kalmykova et al., 2018). Its viability gains global traction due to social, ethical, and ecological benefits, fostering resource-efficient transformation. Diverting industrial by-products into geopolymer concrete production promotes resource conservation and CE (Choudhary et al., 2024).

Geopolymers advance CE and sustainable development (Al-Hamrani et al., 2021; de Azevedo et al., 2021). Their sustainable use, application, and economical production in construction boost employment and energy efficiency (Asim et al., 2021). Projected as a platform for value-added materials, geopolymers achieve economic, environmental, and technological goals. CE thus incorporates environmental mitigation, geological material valorization, and multi-product synthesis using computer-aided modelling (Ucal and Xydis, 2020). Technoeconomic analysis (TEA) guides process design to assess costs and mass/energy balance at the industrial scale. Geopolymers can be marketed as eco-friendly, sustainable water/wastewater treatment materials.

II. Conclusion

Geopolymer concrete emerges as a technically viable and environmentally imperative alternative to OPC, leveraging industrial by-products (fly ash, slag) and natural aluminosilicates to achieve up to 90% lower CO_2 emissions. Its unique polymerization mechanism, yielding amorphous to semi-crystalline N-A-S-H/C-A-S-H gels, confers exceptional mechanical strength (>100 MPa), acid/sulphate resistance, and thermal resilience, enabling applications in demanding environments (e.g., marine structures, fireproofing, sewer rehabilitation). Advanced mix design strategies (e.g., response surface methodology, ANN optimization) address compositional complexity but underscore the need for universal standards. Global case studies (Australia's Well Camp Airport, India's roadways) validate GPC's structural feasibility, while its role in the circular economy through waste encapsulation, water treatment, and resource conservation further amplifies its sustainability credentials. Nevertheless, persistent challenges include efflorescence management, economic viability of activators, supply chain logistics for precursors, and limited long-term performance data. Future efforts must focus on:

- **Standardization:** Developing performance-based codes for diverse precursors.
- **Scalability:** Innovating ambient-cure systems and cost-effective activators.
- **Durability:** Expanding databases on century-long service life predictions.
- **Circularity:** Integrating novel wastes (mining tailings, phosphate sludge) into geopolymer synthesis.

By addressing these gaps, GPC can transition from a promising material to a mainstream sustainable construction technology, aligning with global net-zero ambitions and circular economy principles.

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