2025 Scienceline Publication

Journal of Civil Engineering and Urbanism

Volume 15, Issue 1: 40-64; March 25, 2025

ISSN-2252-0430

DOI: https://dx.doi.org/10.54203/jceu.2025.4

Review of Geopolymer Concrete: Reaction Mechanisms, Mechanical Behavior, and Environmental Benefits

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REVIEW ARTICLE

PII: S225204302500004-15

Received: February 22, 2025

Revised: March 24, 2025

Accepted: March 24, 2025

ABSTRACT

Geopolymer concrete (GPC) presents itself as a sustainable construction material that replaces traditional Ordinary Portland Cement (OPC) concrete by reducing carbon emissions while preserving structural strength and durability. Its strength derives from geopolymerization a chemical reaction in which aluminosilicate-rich industrial by-product (such fly ash, GGBFS, and metakaolin) react with alkaline activators (sodium or potassium hydroxide and silicate solutions) to create a strong three-dimensional aluminosilicate network. This process known as alkali activation transforms raw materials into a strong three-dimensional aluminosilicate network, which consists of silicon and aluminum atoms bonded through oxygen atoms, imparting high strength and chemical stability. The development of gel structure and reaction kinetics depends heavily on the precursor composition, as well as activator concentration, curing regime, and mix design parameters. Nanomaterials such as nano-silica enhance matrix densification and improve early-age strength by filling micro-pores and refining the microstructure. The addition of fiber reinforcements including basalt, polypropylene fibers significantly increase resistance to cracking and improves the material's ductility. Furthermore, the use of tailored aggregates optimizes particle packing, thereby contributing to the overall strength and durability. Recent research indicates that GPC can achieve compressive strength up to 50 Mpa whereas OPC concrete bearly reaches 40 Mpa. Tensile strength improves from about 4.0 to 5.5. Mpa, and flexural strength increases from 6.0 to 8.0 Mpa. Durability of GPC enhanced, with up to 20% demonstrating superior resistance against sulfate attack, chloride ingress, thermal loading, and acidic environments. The paper combines research about rheological optimization and ambient curing feasibility, and shrinkage behavior. The material demonstrates its ability to meet advanced construction needs through its applications in 3D-printed GPC, fiber-reinforced composites and carbon-enhanced formulations. Technology faces ongoing difficulties related to long-term field performance and precursor variability, as well as the absence of unified standards. The long-term field performance of GPC remains insufficiently documented, with uncertainties regarding durability, exposure, such as creep, shrinkage, and resistance to environmental cycles, which could affect the reliability, setting and mechanical properties, posing challenges for quality control and large-scale implementation. To address these issues, further research is needed on extended field trials, standardized characterization of raw materials, and the development of guidelines for mixed design and performance assessment. The review presents current GPC technology developments while identifying essential steps for standardization and scalability, and sustainable infrastructure system integration.

Keywords: geopolymer concrete, mechanism, sustainability, alkali activation, geopolymerization, durability, nanomaterials, fiber reinforcement, standardization

INTRODUCTION

Concrete is the most widely used construction material globally, playing a crucial role in infrastructure development and urbanization. However, its predominant reliance on ordinary Portland Cement (OPC) poses significant environmental challenges. OPC production is responsible for 7–8% of global CO_2 emissions, primarily due to the calcination of limestone and the high energy consumption of kiln firing processes. This contributes to climate change and the depletion of natural resources, highlighting the urgent need for sustainable alternatives in the construction sector (Aleem & Arumairaj, 2012; Turner & Collins, 2013). In response to these environmental concerns, geopolymer concrete (GPC) has emerged as a promising eco-friendly substitute. GPC utilizes industrial byproducts such as fly ash, ground granulated blast-furnace slag (GGBS), and metakaolin, which are rich in silica and alumina, as primary raw materials. Unlike OPC concrete, which gains strength through calcium silicate hydrate formation, GPC achieves its mechanical properties via geopolymerization—a chemical process activated by alkali activators that forms alumino-silicate polymers. This process not only reduces CO_2 emissions by bypassing

To cite this paper: Oumar AI (2025). Review of Geopolymer Concrete: Reaction Mechanisms, Mechanical Behavior, and Environmental Benefits. *J. Civil Eng. Urban.*, 15 (1): 40-64. DOI: https://dx.doi.org/10.54203/jceu.2025.4

clinker production but also promotes waste valorization, aligning with circular economy principles (Sbahieh et al., 2023). The concept of geopolymers dates to the 1970s, introduced by Joseph Davidovits and building on earlier alkaalkali-activated binder research by Kühl and Purdon. Since then, GPC has gained attention for its ceramic-like durability, low energy demand during production, and enhanced resistance to acidic and alkaline environments. These attributes make geopolymer concrete particularly suitable for diverse construction applications, from industrial infrastructure to harsh environmental conditions (Aleem & Arumairaj, 2012; Provis & Van Deventer, 2009). Despite its advantages, challenges remain in op timizing geopolymer concrete formulations. Factors such as mix design, activator position, curing regimes, and long-term durability require further refinement to ensure consistent performance. Recent innovations, including the incorporation of nano-silica and fiber reinforcements, show potential to enhance mechanical strength and durab ility. However, comprehensive real-world studies on these advancements are still limited, indicating a need for conti nued research and development (Matsimbe et al., 2022; Sbahieh et al., 2023).

This study provides a comprehensive review of the current state of geopolymer concrete technology, encompassing its composition, mechanical properties, durability, and practical applications. It addresses recent developments, ongoing challenges, and future directions to promote GPC as a sustainable and viable alternative to conventional OPC-based concrete in modern construction. By bridging existing knowledge gaps, the research seeks to advance the practical adoption of geopolymer concrete, contributing to more sustainable construction practices worldwide. The following section provides an extensive background about geopolymers by studying their scientific development and their position in contemporary construction materials.

Definition and historical development

Geopolymers represent aluminosilicate inorganic materials that emerge through silicon and aluminum-rich raw materials becoming activated by alkali activators under polycondensation processes (Davidovits, 2013; Franco et al., 2022a; Matsimbe et al., 2022). The creation of the term geopolymer stems from French materials scientist Joseph Davidovits during the 1970s. According to his research, mixtures containing alkali activators and calcined kaolin with limestone and dolomite produced these new materials that displayed an Al-Si network structure comparable to natural zeolites (Matsimbe et al., 2022; Provis & Van Deventer, 2009). The term geopolymer was introduced late in history, but scientists, including Kühl and Purdon, had already demonstrated alkali-activated binder concepts in their respective scientific work from 1908 and the 1940s (Pacheco-Torgal et al., 2008). Scientific examination of geopolymers started during the 1980s because scientists sought eco-friendly alternatives to Portland cement (Pacheco-Torgal et al., 2008; Yang et al., 2022). Research on geopolymers has increased because they require minimal energy during production while reducing pollution, together with their ability to incorporate industrial waste such as fly ash and slag as starting materials for manufacturing (Franco et al., 2022a; Provis & Van Deventer, 2009). Several applications exist today for advanced composite materials and waste fixation technologies, thanks to the special combination of properties in geopolymers that mimic ceramics and cement, and basic organic polymers (Davidovits, 1991a; Provis & Van Deventer, 2009; Sbahieh et al., 2023). The historical context serves as a basis to study the chemical reactions that lead to geopolymer formation.

Geopolymerization mechanism and chemistry

Geopolymerization transforms aluminosilicate sources into a strong three-dimensional network because of their fundamental versatility in mechanism and chemistry as illustrated in Figure 1. The initial step of geopolymerization starts with silicon (Si) and aluminum (Al) species from raw materials (such as fly ash, metakaolin, or coal gangue) dissolving highly alkaline solutions containing sodium or potassium hydroxide and silicate solutions (Han et al., 2022). The dissolved species undergo hydrolysis and polycondensation reactions, progressively forming Si–O–Al and Si–O–Si bonds that constitute the amorphous or semi-crystalline aluminosilicate framework (Bakri et al., 2011; Provis & Bernal, 2014). The network structure of geopolymers provides them with their characteristic mechanical strength, together with chemical durability and thermal resistance, which resemble those of ceramics and cement (Davidovits, 2013). The process consists of four distinct phases, which include aluminosilicate source dissolution, followed by dissolved species transportation and orientation, and polycondensation into oligomers before the formation of a continuous gel matrix (Duxson, et al., 2007). The geopolymer gel contains both unreacted particles and secondary phases, which affect its microstructure and performance. The tetrahedral Al network receives stability from alkali cations (Na^+, K^+), which counterbalances its negative charge (Provis & Bernal, 2014). The reaction pathway and final properties remain highly dependent on activator type, concentration, raw material composition, curing conditions, calcium, and other modifiers (Bakri et al., 2011; Khale & Chaudhary, 2007). Geopolymers can function in various applications while immobilizing hazardous waste due to their dense and chemically resistant matrix, which results from complex chemical processes with advanced manufacturing techniques (Duxson, Provis, et al., 2007; Han et al., 2022; Khale & Chaudhary, 2007).

RAW MATERIALS AND ACTIVATORS

Main raw materials

Fly Ash is the most significant byproduct of coal combustion in coal-fired power plants, and it has been identified as a geopolymer concrete precursor raw material because of its high content of Si and Al elements. Al-Si bonded gels are the main component of a geopolymer structure, which is formed by the interaction of fly ash with alkaline solutions. These mechanical properties contribute to the reinforcement of geopolymer concrete (Hardjito & Rangan, 2005; Provis & Van Deventer, 1955-. 2014). Fly ash is widely used as a sustainable, locally available substitute for Portland cement in most countries since it is locally available worldwide, is sustainable, and reduces carbon emissions in landfills (Luhar & Luhar, 2022; Meesala et al., 2020). Research has demonstrated that fly ash geopolymer concrete can attain accelerated strength development, rapid hardening, a glassy microstructure, and increased resistance and durability due to the elimination of hydration reactions or harmful agents. (Palomo et al., 1999; Ryu et al., 2013). Furthermore, the fly ash used to make geopolymer concrete also affects the setting time and the compressive strength levels, and the use of sodium hydroxide as an alkali activator is recommended to attain the optimum compressive strength in geopolymer concretes when compared to the other quartz crystal shapes (Hardjito et al., 2004; Rangan et al., 2008).

Metakaolin: Produced by a hydrothermal treatment at temperatures equal to or below 100°C, for example, the transformation of non-qualified kaolin into a reactive amorphous aluminosilicate precursor is as follows. “Kaolin is calcined at 750 ˚C, which drives off the chemically bound water (hydroxylation) and transforms the material known as kaolinite (a type of clay) into a highly reactive and amorphous aluminosilicate material” (Duxson, et al., 2007; Palomo & Palacios, 2003). This thermal activation prompts the rate of pozzolanic reactivity, and Meta kaolin subsequently serves as a precursor of geopolymer concrete formulations, significantly enhanced, proving Metakaolin as a powerful precursor material in a specially designed geopolymer concrete formulation (Davidovits, 1991b; Provis & Van Deventer, 2009). The material is used to speed up the transition to organic alumina and silica with the subsequent gel formation by alkaline activators. They are strong and rapid aluminosilicate gels that improve the mechanical properties and early strength properties (Bernal et al., 2014; Fernández-Jiménez & Palomo, 2005). Unlike the pure Metakaolin, the fine particle size of Meta kaolin leads to a smaller gap between the particles that in turn allows for a denser structure, lowers porosity, and shrinkage, while severe particle packing occurs in the smaller-than-capillary-pore-size particles. In detailed studies, the temperature and time the calcination is done and how the methyl esters are produced significantly affect the chemical composition and reactivity of Meta kaolin. When the temperature is between 700-850 degrees, the optimum ignition of Meta kaolin would occur concerning the duration (Duxson, Fernández-Jiménez, et al., 2007; Komnitsas & Zaharaki, 2007). According to Singh et al. (2015) and Nath & Sarker (2014), geopolymer concrete can easily be applied in instances when one would require precast pieces. These scenarios facilitate rapid development and enhance durability by resisting sulfate and chloride ingress. The cost of Metakaolin can be higher in comparison with other supplementary materials. However, its enhanced performance makes it a viable option for high-performance and environmentally friendly construction (Provis & Van Deventer, 1955-2014).

Ground Granulated Blast Furnace Slag (GGBFS) is made from the steel-making process. GGBFS is formed through rapid cooling of molten slag to create a glassy granulated material (Juenger et al., 2011; Shi et al., 2018). The fine grinding of GGBFS transforms it into a supplementary cementitious material, which is commonly used together with fly ash and metakaolin in geopolymer concrete mixes (Hardjito & Rangan, 2005; Nath & Sarker, 2014). The calcium content in GGBFS supports the geopolymerization process to create calcium silicate hydrate (C-S-H) and calcium aluminosilicate hydrate (C-A-S-H) gels (Bakharev, 2005; Provis & Bernal, 2014). The gels play a vital role in strengthening the concrete matrix at the initial stages, while shortening the setting time and enhancing both chemical resistance and durability (Fernández-Jiménez & Palomo, 2005; Shi et al., 2018). Geopolymer binders containing GGBFS exhibit superior resistance to sulfate attack and chloride ingress, and alkali-silica reaction, which makes them highly suitable for harsh environmental conditions (Bernal et al., 2014; Juenger et al., 2011). The use of GGBFS in concrete production decreases the environmental impact by minimizing Portland cement requirements (Singh et al., 2023). The performance advantages of GGBFS in geopolymer concrete depend heavily on appropriate design and curing practices (Hardjito et al., 2004; Nath & Sarker, 2014).

1) Alkaline Activators: Sodium Hydroxide and Sodium Silicate

The geopolymerization process requires alkaline activators such as sodium hydroxide (NaOH) and sodium silicate (Na2SiO3) to start and maintain the reaction between aluminosilicate materials and alkali activators (Archana & Abdul Razak, 023). Sodium hydroxide functions as caustic soda to dissolve silica and alumina from aluminosilicate sources, while sodium silicate acts as water glass to create the geopolymer gel network. The SS/SH ratio between sodium silicate and sodium hydroxide determines both workability and compressive strength of geopolymer concrete, which affects the final material performance (Nagajothi & Elavenil, 2018). Higher SS/SH ratios improve workability, but they can negatively impact the development of compressive strength (Sunarsih et al., 2023). The hardened geopolymer concrete benefits from increased Na2SiO3/NaOH ratios, which produce denser and more durable materials (Nikmehr & Al-Ameri, 2022). The increased silica content leads to the development of a stronger geopolymer gel network that enhances both mechanical strength and resistance to degradation. The geopolymerization process, along with concrete properties, depends heavily on alkaline activator concentrations and types, which require exact control of these parameters (Tan Nguyen et al., 2014). The geopolymerization reaction speeds up when alkaline activator concentrations increase, but this can cause material shrinkage and cracking. The selection of appropriate alkaline activators and their concentration must be carefully evaluated to achieve optimal performance of geopolymer concrete for applications (Hamed et al., 2025). Beyond binders and activators, the selection of aggregates and additives further tailors the performance of geopolymer concrete.

2) Aggregates and additives

Recycled Concrete Aggregates (RCA) can be used in geopolymer concrete to reduce the use of virgin aggregates and construction and demolition waste. This approach supports circular economy principles by minimizing resource consumption and reducing waste. However, RCA properties vary depending on source and processing, and this can affect the performance of the geopolymer concrete produced (Abughali et al., 2024; Younis et al., 2020). Manufactured sand (M-sand) made from crushing rocks is a sustainable alternative to natural sand, which is scarce, and has the environmental impact of natural sand extraction, making it a suitable aggregate for sustainable geopolymer concrete (Zhang et al., 2024). Additives like Alccofine, a micro-fine mineral admixture with pozzolanic and reactive properties, improve the fresh and hardened properties of geopolymer concrete even under ambient curing conditions. Alccofine improves workability, density, compressive strength, and durability, it is especially good where high early strength is required or elevated temperature curing is not possible (Bhushan Jindal et al., 2017; Rabie et al., 2022; Chaudhary et al., 2024). Alccofine promotes better polymerization and formation of calcium silicate hydrate (CSH) and related products, which improves the mechanical performance (Bhushan Jindal et al., 2017; Chaudhary et al., 2024). Also, micro-silica (silica fume) and fibers like steel or polypropylene improve the durability of geopolymer concrete by increasing density, tensile strength, and ductility, reducing the cracking and chemical attack. The by-product of silicon production, known as micro-silica, enhances concrete density and strength while fibers serve as reinforcement to stop crack propagation and boost toughness (Bhushan Jindal et al., 2017). The selection and proportioning of aggregates and additives determine fresh and hardened properties of geopolymer concrete, thus making them essential components of mix design. The use of recycled concrete aggregates (RCA) and manufactured sand (M-sand) in concrete production promotes sustainability through virgin material reduction while affecting workability and density, and mechanical strength of the final product. The performance and durability of RCA depend on its source and processing methods, so the mix design needs to be adjusted carefully to achieve consistent results. The rheological behavior and mechanical properties of geopolymer concrete receive additional enhancement through the addition of Alccofine and micro-silica, and steel or polypropylene fibers. The combination of Alccofine with micro-silica increases matrix density and compressive strength, but fibers add ductility and crack resistance, which extends material service life in harsh conditions. The desired workability-mechanical performance-durability balance requires systematic integration of aggregate and additive modifications into the overall mix design strategy. The following section explains how specific mix-proportioning methods optimize material choices to affect both mechanical properties and practical performance of geopolymer concrete in construction applications.

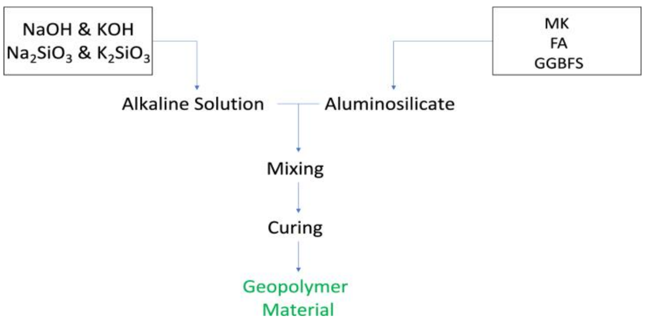

Figure 1. Synthesis of GP cement (Odeh et al., 2024)

Mix Design, Workability, and Rheology

Mix Design and Optimization Methods

The mixed design of geopolymer concrete (GPC) is crucial in determining its strength and durability over time well as its workability, while also aligning with industry standards. It differs from traditional concrete due to the specific blend of aluminosilicate materials like fly ash, metakaolin, or slag, alkali activators such as sodium hydroxide and sodium silicate, water levels, and curing methods involved in the process. The interaction of these factors influences the geopolymerization process that shapes the characteristics of the material (Hardjito et al., 2004; Juenger et al., 2011). The Taguchi method serves as an effective tool for geopolymer concrete mix optimization through statistical analysis, which determines optimal proportions while requiring fewer experimental tests (Anwar et al., 2022). Recent studies have emphasized the significance of these design factors. Basalt fiber inclusion, in metakaolin-based GPC, was found to enhance flexural strengths by Şahin et al. (2021), especially when paired with basalt sand. However, the study identified limitations using recycled waste concrete (RWC) aggregates that lowered strength. This suggests the need for improved mix design approaches when integrating elements such as recycled aggregates to ensure optimal performance in geopolymer concrete (Şahin et al., 2021). Based on these findings, Gopalakrishna and Dinakar (2024) developed a logical and methodical mix design process for fly ash-based GPC using recycled aggregates (RA). Their method provides a substitute for trial-and-error techniques by enhancing critical factors like sodium hydroxide concentration (16M), the ratio of sodium silicate to sodium hydroxide (1.5), and the alkaline activator to binder ratio. Their work proved that recycled aggregates, when used with optimized binder systems, could yield reasonable compressive strengths plus much better durability, where these would be applicable in marine or coastal structures (Gopalakrishna & Dinakar, 2024). Further advancements in mix design optimization were presented by Ansari et al. (2025), who employed a multi-objective optimization framework combining the Taguchi method, Grey Relational Analysis (GRA), and Principal Component Analysis (PCA). This integration approach enables an effective balance of workability, compressive strength, and tensile strength. The optimized mix contained 60% ground granulated blast furnace slag (GGBFS), a low alkaline liquid-to-binder (AL/B) ratio of 0.4, 12M sodium hydroxide, and a sodium silicate-to-sodium hydroxide (SS/SH) ratio of 2.5 are summarized in Table 1, to provide a synthesis and comparative insight into reecent mix design strategies for GPC. Their findings emphasized the critical need to systematically explore interactions among mix parameters to optimize multiple performance criteria simultaneously (Ansari et al., 2025c) (Ansari et al., 2024). The Taguchi method, as demonstrated by Ansari et al., is particularly valuable in GPC research due to its ability to statistically determine optimal mix proportions using orthogonal arrays. This approach reduces the experimental workload while providing robust insights into the influence of individual parameters on concrete properties. It is especially effective in optimizing binder content, activator ratios, and molarity to meet targeted strength and durability goals, which are essential given the reactive nature of alumino-silicate binders (Ansari et al., 2025c). Similarly, Hadi et al. (2019) proposed a simplified experimental procedure to determine the optimum GPC mix under ambient curing conditions. Their method considered compressive strength, setting time, and workability, concluding that a mix containing 40% GGBFS, and AL/B ratio of 0.5, an SS/SH of 2.0, and additional water (Aw/B =0.15) achieved a superior balance of performance attributes compared to Ordinary Portland Cement concrete, while remaining practical for field applications (Hadi et al., 2017, 2019). Their findings alongs with other comparative data, are summarized in Table 2.

Supporting the need for simplified yet scientifically grounded approaches, Gopalakrishna and Dinakar (2023) developed a mixed design methodology based on the specific gravity of constituents and combined aggregate grading standards (DIN). Their study employed a blend of 70% fly ash and 30% GGBFS with 100% coarse aggregate, achieving compressive strengths close to 60 MPa under ambient curing. This demonstrated that accurate proportioning could mitigate the variability inherent in recycled aggregates (Gopalakrishna & Dinakar, 2023, 2024). The limitations of recycled coarse aggregates (RCA), such as high-water absorption, more particle size distribution, and residual cement, make it essential to proportion an appropriate mix to achieve the desired workability and strength while maintaining satisfactory durability. Combining systematic optimization techniques (such as the Taguchi method or PCA) with the basic considerations of material science could provide a guide to producing potential high-performance geopolymer concrete (Gopalakrishna & Dinakar, 2024). This integrated approach is aimed at addressing both the environmental sustainability and structural performance goals.

Table 1. Synthesis and Comparative Insights of mix design of GPC

Geopolymer Concrete Mix Design Optimization

Characteristic	Basalt Fiber Inclusion	Recycled Aggregates	Taguchi Method	Specific Gravity & DIN Standards
Strength Enhancement	Enhanced flexural strength	Reduced strength	Optimal mix proportions	Compressive strengths near 60 MPa
Optimization Focus	Paired with basalt sand	Improved mix design needed	Reduces experimental workload	Mitigates variability
Mix Design	Metakaolin-based GPC	Fly ash-based GPC	Balances workability, strength	70% fly ash, 30% GGBFS
Benefits	Improves bending resistance	Reasonable compressive strengths	Optimizes binder content, ratios	Achieves high compressive strengths

Table 2. Comparative data of different studies mixture and test

Study	Binder system	Aggregate Type	Mix Optimization	Strength (MPa)	Key Features
Şahin et al. (2021)	MK + $NaOH/Na_2SiO_3$	RS, BS, RWS	Fiber % + Aggregate	Up to +25%	BF improved strength, BS > RWC
Gopalakrishna & Dinakar (2024)	FA + $NaOH/Na_2SiO_3$	100% RA	Rational design method	14-35	High durability, systematic design
Ansari et al. (2025)	FA + BFS + $NaOH/Na_2SiO_3$	Natural aggregates	Taguchi + GRA + PCA	73.25 (Opt.)	Multi-objective optimization
Hadi et al. (2019)	FA + GGBFS	Natural aggregates	Mini tests + Empirical	High	Ambient curing, good workability
Gopalakrishna & Dinakar (2023)	FA + GGBFS	100 % RA	New method + DIN/ ACI	~ 60	SG-based method, high early strength

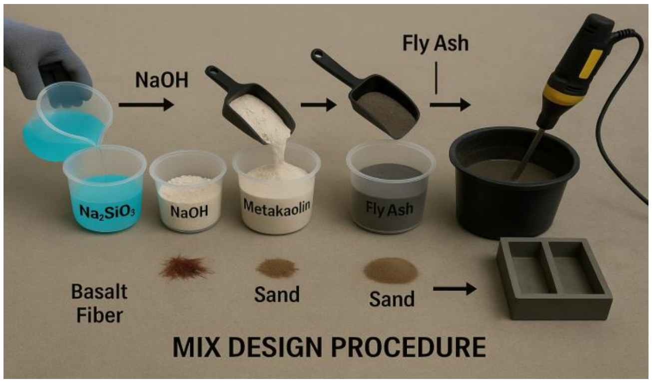

Figure 2. Mix design Procedure.

Rheological properties and workability of geopolymer concretes

The nature of the aluminosilicate material and alkaline activator solution determines the workability, emphasizing the need for material selection to attain a workable mix (Nagajothi & Elavenil, 2018). Flowability and cohesiveness of the mix may be affected by particle size, shape, and surface texture of the aluminosilicate material. The nature and concentration of alkaline activator solutions can also affect workability through the reactivity of the geopolymerization process. Addition of more GGBFS and M-sand will tend to reduce the workability; thus, mixture design must be altered to maintain sufficient flow and consolidation properties (Nagajothi & Elavenil, 2018). GGBFS and M-sand have disparate particle size distributions and surface textures from fly ash, in addition to which they can influence the workability of the mix. Although additives such as superplasticizers can be used to optimize the workability of mixes of high percentage of GGBFS and M-sand. The alkaline liquid to binder ratio impacts on workability of geopolymer concrete where high ratios typically provide enhanced flowability but compromise the strength (Nagajothi & Elavenil, 2018; Vora & Dave, 2013). The alkaline liquid acts as a lubricant, lowers the friction of particles and enhances the mixed flowability. However, too much, or overall alkaline liquid can affect the binder concentration and hence reduce the strength of the formed concrete. Raw Material Council approved certified aggregate-recycled concrete is workability and slump value increasing, which may be useful at certain applications but also needs close control to avoid segregation and bleeding (Periyasamy & Nagarajan, 2024). Addition of RCA can elevate the quantity of solid particles mixture that can enhance workability and slump value. Nevertheless, the felt must be properly graded with the mix in proper ratio to avoid segregation and bleeding.

Effect of Curing Conditions

Temperature

Increased temperatures improve the early reaction of fly ash-based geopolymer concrete, with significant improvement of its early strength development (Ye & Xu, 2014). The added heat supplies the energy to conquer the activation energy barrier of the geopolymerization reaction and higher reaction rate, with increased strength. This is especially so for fly ash-based geopolymer concrete, whose reaction rate is comparatively slow compared to other geopolymer concretes. Curing temperature has an important impact on the physico-mechanical characteristics of geopolymer concrete, which confirms the importance of control over temperature in attaining desired performance properties (Adufu et al., 2023). Whether the curing temperature is too high or too low, the rate and the degree of the geopolymerization reaction, and so the strength, durability, and other properties of the concrete, are affected. Consequently, it is critical to carefully monitor the curing temperature to achieve the required performance criteria for concrete. An optimal temperature of 70°C is adequate for curing self-compacting geopolymer concrete mixed with GGBFS and RHA (Rice Husk Ash), a combination of strength development and energy cost (Patel & Shah, 2018). Such a temperature is favorable to require a fast geopolymerization reaction without exerting extreme drying or cracking of the concrete. Also, the utilization of GGBFS and RHA in combination can help in strength, development, and durability in concrete. Elevated temperature may cause surface deterioration if not over, and it could call for careful monitoring and control when it comes to the curing process (Niveditha & Koniki, 2020). A large amount of heat can result in an increased rate of evaporation of water, which causes shrinkage cracking and may also reduce durability. Hence, keeping a controlled temperature and humidity during the process of curing helps to avoid surface deterioration.

Humidity

Appropriate steam curing will prove helpful for fly ash-based geopolymer concrete in terms of strength development, as it will create a humid atmosphere conducive to the geopolymerization reaction (Ye & Xu, 2014). The steam facilitates a continuous supply of moisture, which avoids concrete dehydration, thus enhancing the geopolymerization reaction to completion. This is especially critical to fly ash-based geopolymer concrete, which normally has a slower rate of reaction in comparison to other geopolymer concrete compositions, which typically have a faster rate of reaction. It is also evident that ambient-cured specimens are more prone to higher density and drying shrinkage than during oven-curing due to different reaction mechanisms and microstructural development of the materials under different curing conditions (Chouksey et al., 2022). Ambient curing produces a slower reaction, resulting in a microstructure that is denser with greater drying shrinkage. Oven-cured, however, increases the reaction to run faster, hence producing a microstructure as dense as drying shrinkage.

Humidity curing is essential for cast-in-situ provision, allowing sufficient moisture for the geopolymerization reaction to occur in situ applications (Nuruddin et al., 2011). In-situ conditioning may be difficult to handle at times because the temperature and humidity levels change, thus the need to ensure proper moisture for minimizing the moisture loss and the presence of dry concrete. It can be done using moistened burlap, plastic sheeting, or other methods of retaining moisture. Under high humidity, there is reduced moisture loss at early curing stages, leading to improved compressive strength (Nuruddin et al., 2011). Moisture is required for the geopolymerization reaction, and loss of moisture can be prevented so that the reaction can be more complete, and the strength to be improved. This is even more important in hot and arid weather, where moisture loss may be extremely quick.

Steam and oven curing

Oven curing tends to give better compressive strength, indirect tensile strength, and modulus of rupture than ambient curing because of the increased rate of reaction at the elevated temperatures involved (Chouksey et al., 2022; Parveen et al., 2018). The rise in temperature supplies the energy required to overcome the activation energy barrier of the geopolymerization reaction, so that the reaction rate is enhanced, and strength is increased. This is especially important to realize high early strength in geopolymer concrete. Elevated temperature curing is critical for the strength development of fly ash geopolymer concrete because fly ash reacts more slowly at lower temperatures (Polusani et al., 2022). The temperature is high enough, therefore, to offer the required energy to activate the fly ash and generate the geopolymerization reaction. Elevated temperature curing is necessary for fly ash geopolymer concrete to attain the full-strength design. Enhanced curing time improves the geopolymerisation process, where full strength is accomplished, concerning the time given for the work to proceed to completion (Aleem & Arumairaj, 2012; Nurruddin, 2018). The geopolymerization reaction is time-dependent, and a longer time for the reaction to be completed results in a complete reaction and higher strength. Optimal curing time depends on the mixed design and curing conditions. Curing at 90°C for 72 HR is suitable for FA-based mixtures with varying GGBFS contents – a standardized curing regime for assessing the performance of these mixes (Yazıcı & Karagöl, 2024). This curing regime enables consistent comparison of properties of different mixes, useful for optimization of mix designs. The composite of fly ash and GGBFS has the potential to produce overlying actions leading to enhanced strength, durability, and ease of working of the concrete.

Ambient conditions

Geopolymer concrete curing at ambient conditions is more eco-friendly and energy-saving compared to steam or oven curing because it does not require any external heating and cuts down the energy utilized in production (Rabie et al., 2022; Zhang et al., 2024). This curing method waits for the ambient temperature and moisture to start the geopolymerization process (Zannerni et al., 2020). However, because externally facilitated heating is not available, the chemical processes slow down, and the strength achieved is much lower compared to samples cured at higher temperatures (Kumar Yierlapalli et al., 2023). Enhancing the properties of geopolymer concrete cured at ambient temperatures can be achieved by adding Alccofine, which acts as a nucleation agent that speeds up geopolymerization, encouraging a denser and more uniform microstructure, which improves early strength. While ambient curing may be appropriate for many practical applications with low to moderate strength requirements, controlling the mixed design and curing parameters is key in maximizing the performance of ambient geopolymers (Nath & Sarker, 2012; Sam & Deepa, 2018).

MECHANICAL PROPERTIES AND STRENGTH DEVELOPMENTS

Understanding the mechanical behavior of geopolymer concrete (GPC) is essential to ensure it meets both structural and environmental performance targets. This section evaluates the critical strength metrics of GPC compressive and tensile under varying curing conditions, activator concentrations, and material compositions (Mohammed et al., 2021). Geopolymers concrete exhibits distinctive mechanical characteristics due to its unique chemical structure and curing mechanisms. These properties determine its reliability and sustainability in modern construction applications. The key mechanical attributes of GPC are explored in the following subsections (Mohammed et al., 2021; Murali, 2024).

1.1. Compressive Strength of GPC

Compressive strength in geopolymer concrete is primarily governed by curing temperature, mix design ratios, and the chemistry of the aluminosilicate and alkaline components. Elevated curing temperatures and controlled humidity significantly enhance the rate and extent of geopolymerization, thereby improving strength development (Tan Nguyen et al., 2014; Ye & Xu, 2014). The concentration of alkaline activators, particularly sodium hydroxide (NaOH) molarity, plays a critical role. Higher NaOH molarity up to an optimum level facilitates more effective activation of fly ash or metakaolin, improving compressive strength. However, excessively high concentrations may lead to micro-cracking and increased shrinkage, which degrade mechanical performance (Waqas et al., 2021). The inclusion of nano-silica as a supplementary additive contributes to improved matrix densification. Acting as a nano-filler, nano-silica refines the microstructure, reduces porosity, and enhances the strength of GPC (Mansourghanaei, 2023). Fiber reinforcement, particularly with basalt fibers, has also demonstrated tangible benefits. Sahin et al. (2021) reported that incorporating 0.8–1.2% basalt fibers by volume improved compressive strength by up to 23%, in addition to enhancing workability and fracture toughness (Şahin et al., 2021). Aggregate selection further influences performance. Basalt aggregates offer superior compressive strength due to their density and hardness, while recycled concrete aggregates (RCA), though sustainable, may reduce strength due to their porosity. This drawback can be mitigated by fiber reinforcement (Şahin et al., 2021). Optimizing curing conditions, activator composition, nano-additives, and aggregate type are essential for maximizing the compressive strength of GPC (Şahin et al., 2021; Ye & Xu, 2014).

While compressive strength defines GPC's load-bearing capacity, tensile strength is equally crucial for evaluating its resresistance to cracking and its performance under flexural stresses.

Tensile and Splitting Strength of GPC

Geopolymer concrete exhibits notable tensile propert ies, which are typically measured using the splitting tensile strength method. This test involves applying compressive loading along the diameter of a cylindrical specimen and provides insight toward the material's ability to resist cracking (Chouksey et al., 2022; Verma & Dev, 2022). Mix design and curing conditions significantly influence tensile performance. The selection and proportioning of constituents affect chemical composition and packing density, while curing temperature and humidity impact the rate of geopolymerization. Incorporating fibers such as polypropylene enhances tensile strength by bridging crack s and improving crack resistance (Wong, 2022). Research on sawdust ash-blended GPC has identified optimal concentration ratios for NaOH, Na_2SiO_3/NaOH, and other parameters that achieve enhanced tensile performance. These findings are valuable for designing sustainable concrete suitable for structural applications (Gift et al., 2024). In addition, studies examining the performance of GPC at elevated temperatures indicate that well-formulated mixes maintain tensile integrity under extreme conditions. This makes GPC a viable candidate for fire-resistant construction (Pratap & Kumar, 2024; Singh Rajput et al., 2024). Such insights help tailor mix designs f or specific structural and environmental demands, including resilience against thermal stress and long-term durability. Together, compressive and tensile strength analyses affirm the structural viability of geopolymer concrete as summarized in Table 3. By optimizing mix design variables, incorporating suitable additives and fibers, and selecting appropriate curing methods, GPC can be engineered to meet or exceed conventional performance standards, offering a robust and sustainable alternative to Portland cement concrete.

Flexural Strength

Flexural strength, a measure of the concrete's ability to resist bending forces, is enhanced by the inclusion of recycled steel fibers, which act as reinforcement and improve the concrete's ability to withstand tensile stress (Alobeidy & Khalil, 2024). Recycled steel fibers bridge the cracks that form in the concrete under bending loads, preventing them from propagating and increasing the concrete's load-carrying capacity. Oven-cured specimens have a higher modulus of rupture than ambient-cured specimens, as the elevated temperature promotes a more complete geopolymerization process and results in a denser and more homogeneous microstructure (Chouksey et al., 2022). The higher density and homogeneity of the over-cured specimens contribute to their improved resistance to bending forces. Flexural strength can be estimated using empirical equations related to compressive strength, providing a convenient way to assess the flexural performance of geopolymer concrete based on its compressive strength (Verma & Dev, 2022). These equations are typically derived from experimental data and can be used to predict the flexural strength of geopolymer concrete with reasonable accuracy. The modulus of rupture increases with higher steam curing temperatures, as the increased thermal energy promotes a more complete geopolymerization process and results in a stronger and more durable concrete (Ujianto et al., 2024).

Improving the damping properties of geopolymer concretes is critically important for overcoming the disadvantages of conventional concrete, such as low tensile strength and low ductility. In this context, the incorporation of fibers and additive materials enhances the dynamic performance of structures, enabling the achievement of a higher damping ratio. The Half-Power Method, which is based on the frequency spectrum of structural acceptance, serves as an effective tool for calculating this damping ratio. It has been shown that the ratio obtained by determining the upper and lower frequency values has positive effects on structural health and durability (Doğan et al., 2022). The effects of CF content on damping from the study results of Doğan et al. are given in Fig. 3.

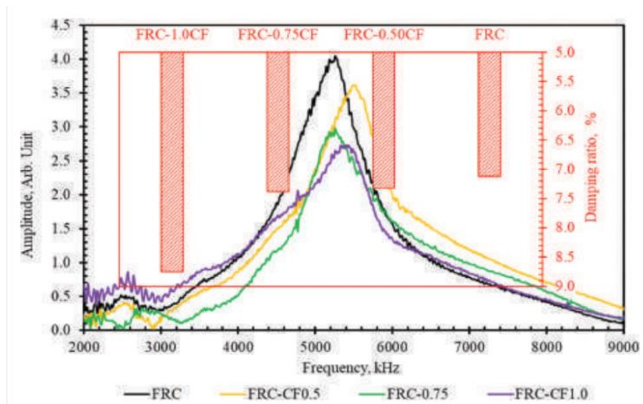

Figure 3. Damping ratio and amplitude-frequency curves (Doğan et al., 2022).

Table 3. Comparative table of Compressive and Tensile Strengths of Geopolymer Concretes

Authors	Geopolymer type / Mix details	Compressive Strength (MPA)	Tensile Strength (MPA)	Test Methods	Reference
Li et al. (2019)	Review: Fly ash/slag-based GPC (various mix designs)	25 - 80	2.0 – 5.0 (typical range)	Compressive: Cube/cylinder Tensile: Splitting, Flexural	(N. Li et al., 2019)
Aziz et al. (2023)	POFA-based geopolymer concrete	20 - 40	2.0 – 3.0	Compressive: Cube test Splitting tensile: Cylinder splitting	(Pratap & Kumar, 2024)
Kumar et al. (2024)	Metakaolin-based geopolymer concrete	40 - 70	2.5 – 3.8	Compressive: Cube test Flexural/tensile: Flexural beam or splitting tensile	(Gift et al., 2024)
Zhang et al. (2022)	Fiber-reinforced geopolymer composites	30 - 60	3.5 – 5.2	Compressive: Cube test Tensile: Direct tensile test	(Wong, 2022)
Dev et al. (2020)	Fly ash/GGBFS-based geopolymer concrete	25 - 55	2.8 – 3.6	Compressive: Cube test Splitting tensile: Cylinder splitting	(Verma & Dev, 2022)
Sahin et al. (2021)	Geopolymer concrete with recycled aggregates	35 - 62	2.2 – 3.4	Compressive: Cube test Splitting tensile: Cylinder splitting	(Şahin et al., 2021)

Early and long-term strength development

Elevated temperature accelerates the early reaction, which is conducive to strength by promoting a faster rate of geopolymerization and leading to a more rapid development of compressive strength in the early stages of curing (Singh Rajput et al., 2024). The increased thermal energy provides the necessaryactivation energy for the chemical reactions to occur, resulting in a more rapid formation of the geopolymer gel network (Verma and Dev 2022). Longer curing times enhance the geopolymerization mechanism, leading to high strength and improved durabilityty over time (Nurruddin et al., 2018). This extended curing period allows for a more complete reaction between the aluminosilicate materials and the alkaline activator solution, producing a denser and more robust microstructure. The incorporation of binary or ternary blends improves crucial properties and enhances early strength development, as the different materials in the blend complement each other and promote a more efficient geopolymerization process (Singh et al., 2015). For instance, a blend of fly ash and ground granulated blast furnace slag (GGFBS) can provide a balance be tween early-age strength and long-term durability. Long-term strength development is influenced by the mixture of components and curing conditions, with the type of aluminosilicate material, the alkaline activator solution, an d the curing temperature and humidity all playing significant roles (Ansari et al., 2025a). Therefore, selecting appropriate materials and curing conditions is crucial for achieving the desired long-term strength and durability of geopolymer concrete (Noh et al., 2025).

It is possible to produce geopolymer repair mortar using carbon-based nanomaterials, as in traditional cementitious materials. In the study conducted by Dehghanpour et al., it was aimed to investigate the production and performance of cement-based repair composite (CBRC) using gels containing nano-Al_2O_3 (NAl), carbon nanotubes (CNTs) and carbon fibers (CF). Carboxymethyl cellulose (CMC) powder, which has high dispersion and suspension properties, was used as an additive material in gel production. Various CBRC samples were produced by adding gels prepared in different mixtures to Portland cement. In order to evaluate the mechanical properties of these samples, compressive strength, flexural strength, splitting tensile strength and surface hardness tests were performed. The obtained results showed that the reinforcing particles provided significant improvements on mechanical strength. The microstructure, elemental composition and crystal phase structure of CBRC were analyzed in detail by scanning electron microscope (SEM), energy dispersive X-ray spectroscopy (EDS) and X-ray diffraction (XRD) methods. SEM images revealed that CBRC has a dense microstructure. In addition, it was determined that NAl particles concentrated at the cement paste interface and contributed by filling the voids. It was emphasized that the strong bonds formed by the reinforcement materials contributed greatly to the development of the mechanical properties of the mortar. It was suggested that the combination containing CNT, Al_2O_3 and CF, which provides the highest compressive strength, should be preferred (Dehghanpour et al., 2022).

Shrinkage behavior

Drying shrinkage in geopolymer mortars can sometimes be slightly higher than that observed in conventional cementitious systems; however, it can be effectively minimized through careful mixture optimization and the incorporation of appropriate additives (Chouksey et al., 2022; Deng et al., 2025). Drying shrinkage is the reduction in volume that occurs as c oncrete loses moisture to the environment, which can lead to cracking and reduced durability if not properly controlled (Deng et al., 2025; Islam et al., 2017). Controlling the water-to-binder ratio and selecting suitable aluminosilicate precursorsare critical factors in reducing drying shrinkage in geopolymer systems (Islam et al., 2017). The use of shrinkage-reducing admixtures have SRAs, such as polyol-based SRAs, and fibers has been shown to significantly mitigate shrinkage-induced cracking by improving the microstructure and restraining volume changes (Zhang et al., 2023). Moreover, curing conditions such as humidity and temperature play a vital role in influencing drying shrinkage, withthe optimized curing regimes helping to reduce shrinkage strains and enhance durability (Wallah, 2009). Therefore, a combination of mixture design optimization, additive incorporation, and controlled curing is essential to minimize drying shrinkage and ensure the long-term performance of geopolymer concrete (Islam et al., 2017).

MICROSTRUCTURE AND MATERIAL CHARACTERIZATION

Microstructure analysis techniques

Characterizing the microstructure of geopolymer concrete (GPC) is crucial for understanding its mechanical behavior, durability, and overall performance. Among the various analytical techniques, Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), and Fourier Transform Infrared Spectroscopy (FTIR) are extensively employed to provide complementary insights into the morphology, crystalline phases, and chemical bonding within geopolymer matrices (Bohra et al., 2020; Das & Rout, 2021). A foundational SEM analysis was presented by Fu et al. (2021), who highlighted the core transformation during geopolymerization through the breakdown of fly ash spheres and the subsequent formation of amorphous aluminosilicate gels. Their images clearly illustrated how the dissolution and re-polymerization processes contribute to improved matrix continuity and densification (Fu et al., 2021) as shown in Figure 5. Expanding upon this, Shi et al. (2012) used SEM combined with Energy Dispersive X-ray (EDX) spectros copy to analyze alkali-activated fly ash-based recycled concrete. Their results indicated a notable reduction in Portlandite and pore voids, with a more homogeneous matrix due to the presence of amorphous aluminosilicate gels. This confirmed the effectiveness of geopolymerization in strengthening the internal matrix stru cture (Assi et al., 2018; Shi et al., 2012). The ambient-cured SEM observations of wateree, McMeekin, McMeekin Spherix 50, and McMeekin Sperix 15 fly ash are presented in Figure 6. A similar focus on microstructure improvement was taken by Assi et al. (2018), who investigated the effect of fly ash particle size. Their SEM observations revealed that finer particles led to fewer microcracks and voids, suggesting improved reactivity and a denser matrix structure. This emphasizes the critical role of raw material fineness in enhancing geopolymer concrete quality (Assi et al., 2018).

Moving to multi-component systems, Bouaissi et al. (2019) examined geopolymer concrete synthesized from FA-GGBFS-HMNS blends. Their SEM images depicted a highly compacted and cohesive matrix with strong intermolecular bonding, which was directly linked to the improved mechanical strength observed in their compressive tests (Bouaissi et al., 2019). Curing effects on microstructural evolution were explored by Lee et al. (2019). Representative SEM images of FA-based geopolymer pastes are ulustrated in Figure 8. After 180 days of indoor and outdoor curing, SEM analysis showed a uniform, densely packed matrix with reduced porosity, highlighting the beneficial role of long-term curing on microstructural stability retention (Lee et al., 2019). The SEM image of GCW5 geopolymer concrete after 180-day outdoor curing is given on Figure 7. Addressing fiber reinforcement, Lee et al. (2022) conducted a detailed SEM investigation of fiber-reinforced geopolymer concrete. The images demonstrated crack-bridging behavior and strong interfacial bonding between fibers and matrix. This microstructural integrity contributed to better crack control and enhanced durability in corrosive environments (Li et al., 2022). Chemical activator influence was examined by Shilar et al. (2022), who studied the effect of varying molarity on geopolymer microstructure. SEM analysis revealed that higher activator molarity produced denser, more continuous matrices, attributed to accelerated and more complete geopolymerization kinetics (Shilar et al., 2022).

A comparative analysis between geopolymer and Portland cement-based systems was conducted by Pereira et al. (2018). Their SEM observations revealed that geopolymer concrete exhibited fewer pores and a more homogeneously bonded structure than traditional Portland systems, supporting the environmental and performance benefits of geopolymer alternatives (De Pereira et al., 2018). Comparative SEM micrographs of OPC and GPC are provided in Figure 9. Further refinement of microstructure through additives was presented by Mustakim et al. (2020). Field emission SEM analysis demonstrated that incorporating nano- and micro-silica into FA-GGBFS concrete significantly refined the pore structure, minimized microcracking, and led to the formation of a densely packed geopolymer gel network (Mustakim et al., 2021). Lastly, Bellum et al. (2022) reinforced this trend by showing that FA-GGBFS geopolymer samples displayed continuous gel phases and a well-structured interfacial transition zone (ITZ) in SEM images. These features were solely responsible for enhanced mechanical strength and improved resistance to degradation (Bellum et al., 2022).

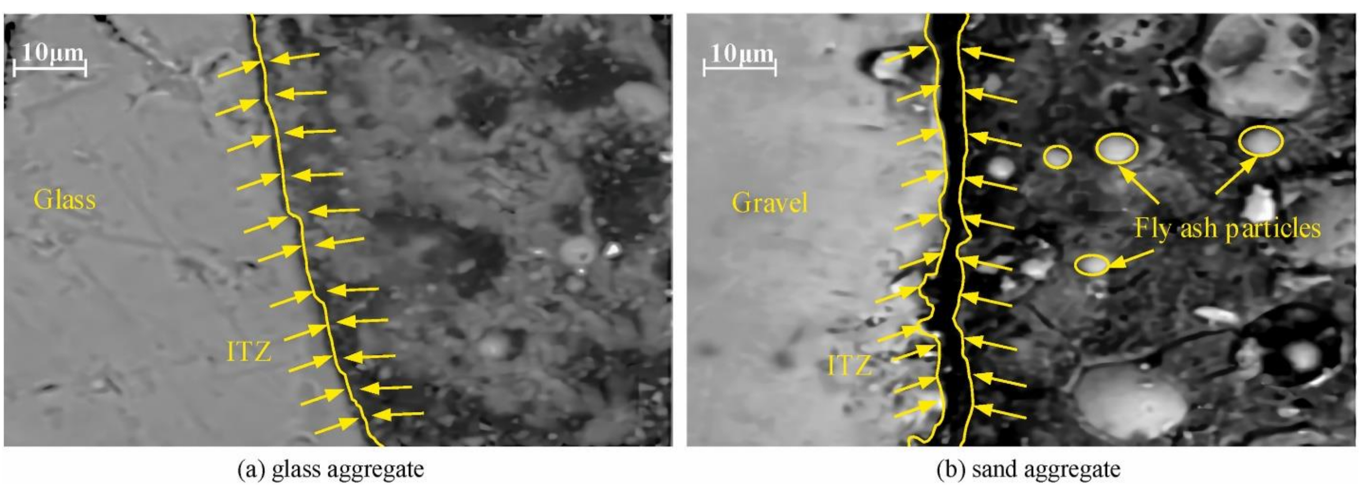

Figure 5. SEM images of the interface transition zone between the geopolymer matrix and different aggregates (Fu et al., 2021).

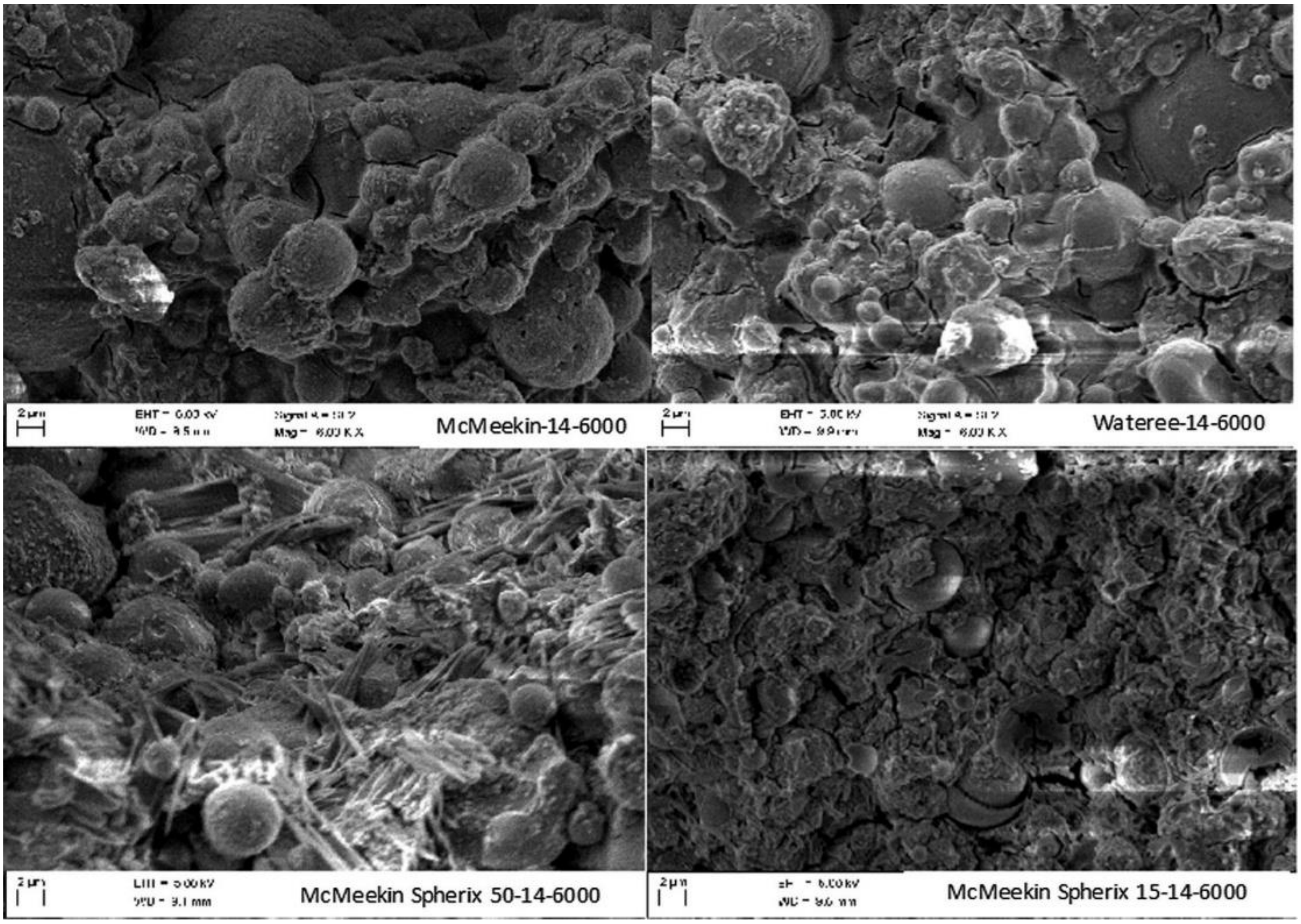

Figure 6. Ambient-cured SEM observations of Wateree, McMeekin, McMeekin Spherix 50, and McMeekin Spherix 15 fly ash (Assi et al., 2018).

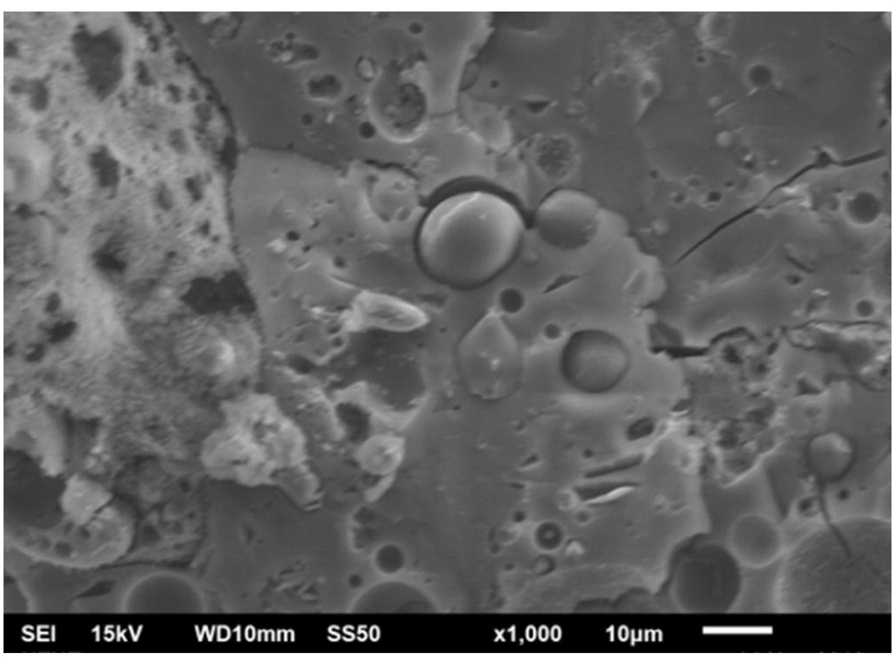

Figure 7. SEM image of GCW5 geopolymer concrete after 180-day outdoor curing (Lee et al., 2019)

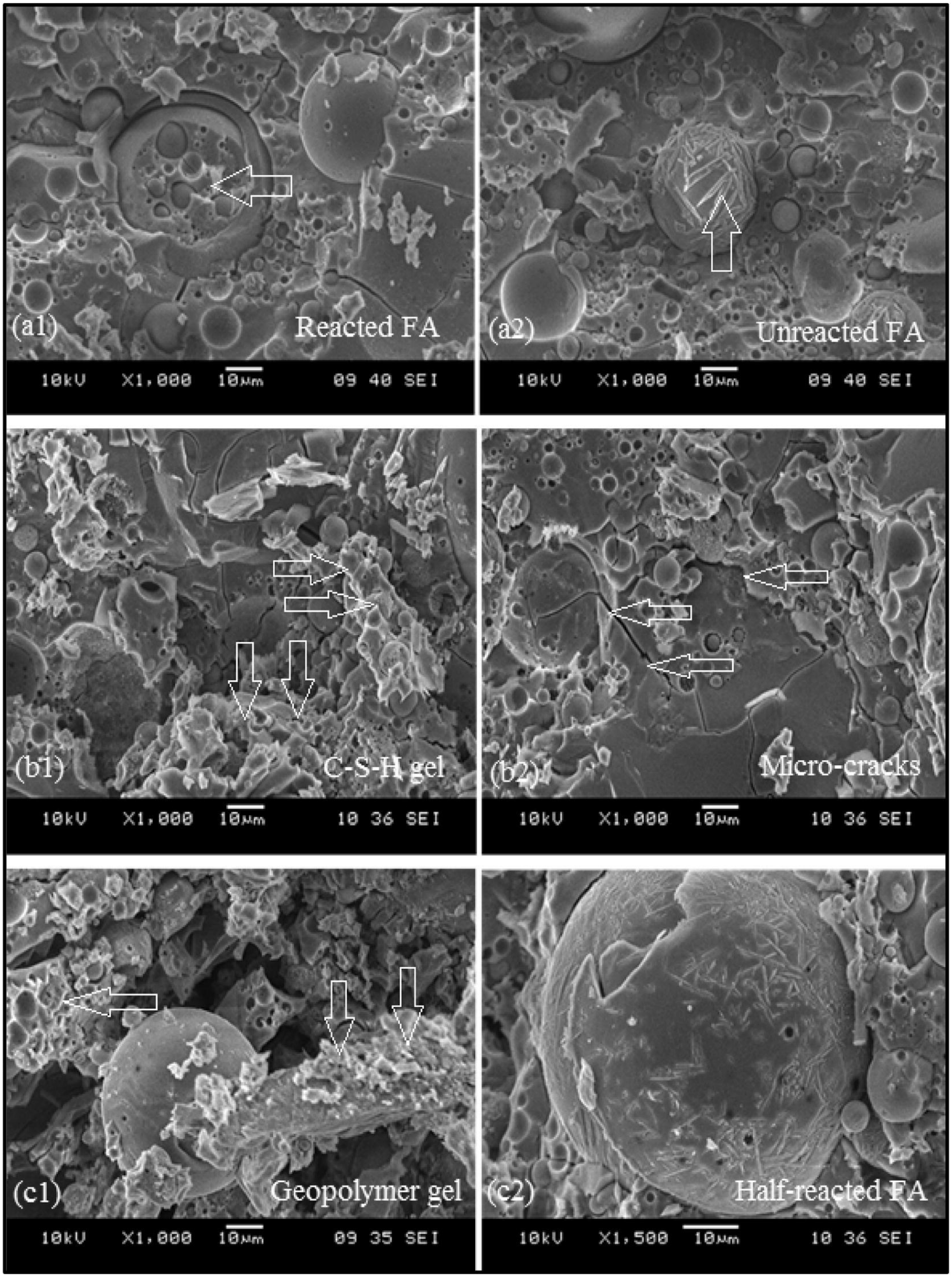

Figure 8. SEM images of FA-based GP pastes (Bouaissi et al., 2019).

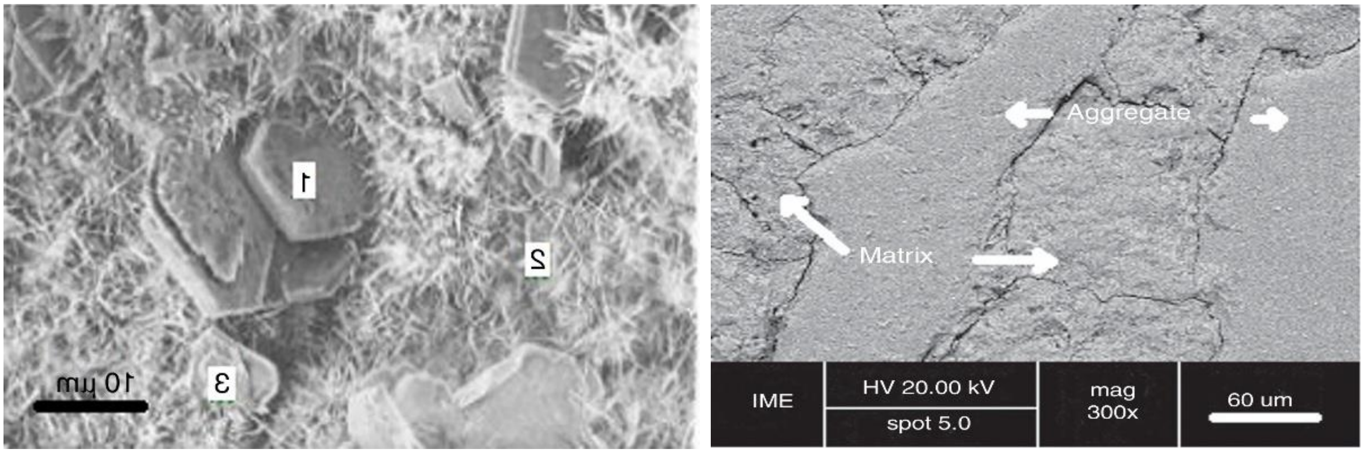

Figure 9. a) SEM micrograph of Portland cement concrete; b) EM-BSE micrograph of geopolymer concrete (De Pereira et al., 2018).

Influence of nanomaterial reinforcement

The use of nanomaterials in improving the mechanical properties of geopolymer concrete (GPC) has become an area of interest, especially in its compressive and flexural strength. One of the most extensively studied nanomaterials is nano-silica, which has particle sizes between 1 to 100 nanometers and possesses a remarkable surface area, thus enabling efficient chemical interaction with the geopolymer matrix (Petermann et al., 2010). Nano-silica is also known to improve the density and homogeneity of the matrix, which enhances strength and durability. Beyond nano-silica, carbon-based nanomaterials like CNTs and graphene have garnered considerable attention for their potential to enhance geopolymer composites. Carbon nanotubes (CNTs) are cylindrical carbon molecules arranged in a hexagonal lattice and exhibit exceptional tensile strength and stiffness. One main issue with CNTs is their tendency to agglomerate due to van der Waals forces, which poses a significant challenge for achieving dispersion within the geopolymer matrix. Methods such as sonication and surface modification have been devised to address this gap and improve the reinforcing efficiency of CNTs (AlTawaiha et al., 2023). Additionally, graphene, a two-dimensional sheet of carbon atoms, stands out as an attractive secondary reinforcement material due to its exceptional strength, stiffness, and impermeability. Achieving homogeneous dispersion of graphene, like CNTs, is equally important and can be enhanced through surface treatments and the application of dispersants (Qamar et al., 2024; Thostenson et al., 2001).

The development of hydrophobic characteristics in geopolymer concrete offers a promising avenue for enhancing the durability and water resistance of constructions involving such materials. Geopolymer concrete is traditionally known for its high porosity and susceptibility to liquid diffusion. To address this, surface treatments can impart hydrophobic properties, similar to those observed in mortars enhanced with hydrophobic additives such as TiO2 and ZnO (Meskhi et al., 2023). The modification of surface characteristics through these additives can result in significant increases in contact angles, enhancing water repellency, which is essential for preventing the ingress of harmful substances (Yazid et al., 2022 and Doğan & Dehghanpour, 2021). An example image representing the hydrophobic properties on cementitious materials is given in Figure 10. Studies have indicated that incorporating materials like TiO2 can achieve contact angles exceeding 136 degrees, which greatly reduces moisture absorption by creating a barrier against liquid diffusion, although specific values for different formulations may vary (Sherwani et al., 2022). Furthermore, the use of recycled materials, such as carbon additives, has shown that low-cost materials can effectively impart hydrophobic properties, albeit the reported contact angles may vary based on the specific dosage and formulation. This reflects an important trend where not only the mechanical performance of geopolymer concrete is enhanced but also its environmental footprint by incorporating sustainable materials.

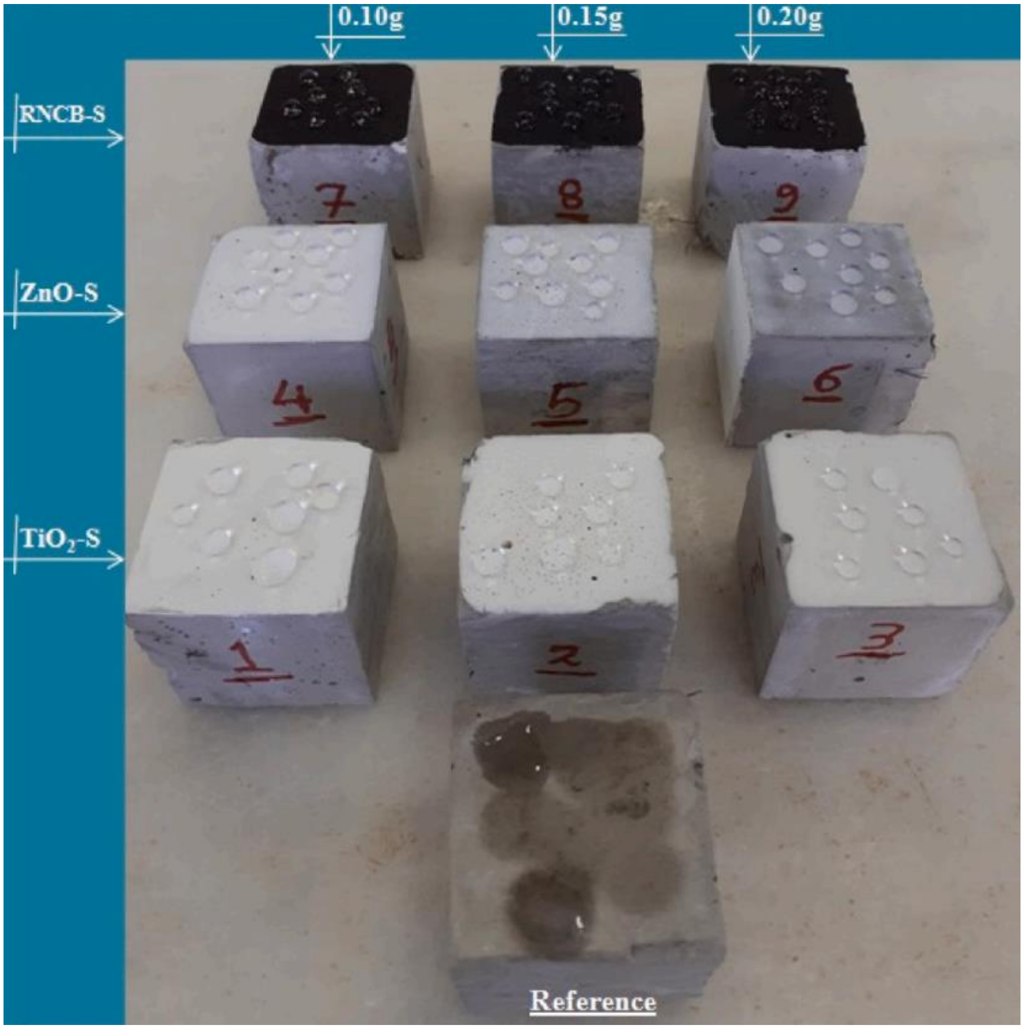

Figure 10. The response of hydrophobic surfaces to water drops; TiO2–S (1–3), ZnO–S (4–6), RNCB-S (7–9) and pure specimen (single).

Durability and environmental performance

In comparison to other types of concrete, geopolymer concrete is renowned for its remarkable durability in aggressive environmental conditions. However, there is still a need to optimize its freeze-thaw resistance for application in cold climate regions. Numerous factors affect freeze-thaw durability, including but not limited to the type and amount of pozzolanic materials used, sodium silicate concentration, fiber type and length, and activator chemistry (Shamsa et al., 2019; Zhou et al., 2024). Metakaolin-based geopolymers, for instance, have been shown to withstand between twenty and fifty freeze-thaw cycles; however, their frost resistance overall is lower than that of conventional Portland cement concrete, which is below seventy-five cycles, with over seventy-five cycles being the failure threshold norm (Aygörmez & Aygörmez, 2021; Pilehvar et al., 2018). Enhancements in freeze-thaw durability have been associated with greater slag concentration, improvements in the Na2O equivalent balancing, activator modulus, and use of air-entraining agents. These improvements assist in reducing permeability and increasing the mechanical properties, thus decreasing freeze-thaw damage (Lingyu et al., 2021). The principal controlling factors of a GPC freeze-thaw failure are hydrostatic and osmotic pressures that are influenced by pore saturation and the salt crystallization pressure in the microstructure (Bumanis et al., 2022). From the experimental observations, metakaolin, fly ash, and slag-based geopolymer concretes exhibit high relative dynamic modulus and high compressive strength even after 28 to 300 cycles of freeze-thaw, frequently exceeding or equalling Portland cement concrete under comparable conditions (Min et al., 2022).

Geopolymer concretes have also demonstrated lower freeze-thaw resistance; however, in addition to that, they tend to have greater resistance to sulfate attacks due to their dense microstructure and low permeability. Metakaolin-based geopolymers offer effective protection against further deterioration in highly sulfate-activated environments like 10% MgSO4 solution over time, while sustaining reasonable compressive strength (Bumanis et al., 2022; Lingyu et al., 2021). Furthermore, enhanced carbonation resistance in geopolymer concretes is critical for preserving the high alkalinity necessary to protect embedded steel reinforcement from corrosion, thus ensuring long-term structural integrity in carbonation-prone environments (Lingyu et al., 2021). Collectively, these durability characteristics underscore the potential of geopolymer concrete as a sustainable and resilient alternative to conventional concrete, particularly in harsh environmental conditions where freeze-thaw cycles, sulfate exposure, and carbonation pose significant challenges (Aygörmez & Aygörmez, 2021).

Specialized geopolymer concrete types

To meet specific engineering requirements and expand the applications of geopolymer technology, advanced forms of geopolymer concrete have been developed. Among these, fiber-reinforced geopolymer concretes (FRGC) have shown significant improvements in mechanical properties and durability. Franco (2022) and Mohamed and Zuaiter (2024) noted that glass fibers enhance the laminate's tensile and flexural strength as well as impact resistance, while also improving tensile and crack resistance (Franco et al., 2022b; Mohamed & Zuaiter, 2024). Basalt fibers, which are naturally occurring from volcanic rocks, provide high strength, a high modulus of elasticity, and excellent chemical resistance, which is particularly beneficial in enhancing an FRGC's freeze-thaw resistance and overall durability in harsh environments (Franco et al., 2022b). In addition to fiber reinforcement, geopolymer mortars have been developed for 3D printing. These mortars feature rapid setting times, high early and ultimate strength, and workability, all of which are essential during layer-by-layer additive manufacturing. The use of geopolymer mortars in 3D printing allows for geometric customization of building elements, reducing material and labor costs, and promoting sustainability and efficiency in construction (Ranjbar & Zhang, 2020). Furthermore, the incorporation of carbonized materials, such as biochar and activated carbon, is of interest for added functionality in geopolymer composites. Biochar, a product of biomass pyrolysis and a carbonaceous substance, enhances water retention, thermal insulation, and mechanical properties by acting as a pozzolanic material that reacts with calcium hydroxide to produce strength-enhancing compounds, alongside the valorization of agricultural waste as simultaneous benefits (Mohamed & Zuaiter, 2024). The application of activated carbon, with its high porosity and surface area, has improved geopolymer concrete in terms of adsorption capacity, electrical conductivity, and mechanical strength, potentially increasing its use in environmental technological remediation and multifunctional construction materials (Mohamed & Zuaiter, 2024). Overall, these purpose-designed types of geopolymer concrete demonstrate the flexibility and adaptability of geopolymer technology to address specific needs in a range of engineering challenges, from enhanced durability and load-carrying behavior to sustainability and environmental functionality.

Geopolymer concretes, synthesized from aluminosilicate-rich industrial by-products, offer a sustainable alternative to traditional cementitious materials due to their lower carbon emissions and superior durability. Recent advancements in functionalizing these systems for electrical conductivity have opened new avenues in smart infrastructure. Dehghanpour and Yilmaz (2020) demonstrated that incorporating conductive materials into concrete enables effective heat distribution, particularly in applications such as self-heating pavements and de-icing systems. Their study further emphasized the role of rebar reinforcement in enhancing the thermal response of conductive concretes. Building on these insights, Dehghanpour (2023) explored the synergistic use of carbon nanotubes and carbon fibers in cementitious surface coatings to achieve enhanced electrical conductivity and refined microstructural characteristics. This approach suggests that similar strategies could be effectively applied to geopolymer matrices, which possess a highly reactive and binding-rich structure suitable for dispersing conductive fillers. By integrating nanomaterials like carbon nanotubes into geopolymer systems, it is possible to develop next-generation conductive geopolymers with multifunctional capabilities, including structural health monitoring, electromagnetic shielding, and thermal regulation. Therefore, the convergence of geopolymer technology and conductive composite research represents a promising direction for sustainable and intelligent construction materials (Dehghanpour, 2023; Dehghanpour & Yilmaz, 2020). An example image of the test setup for resistivity measurement of electrically conductive concretes is given in Figure 11.

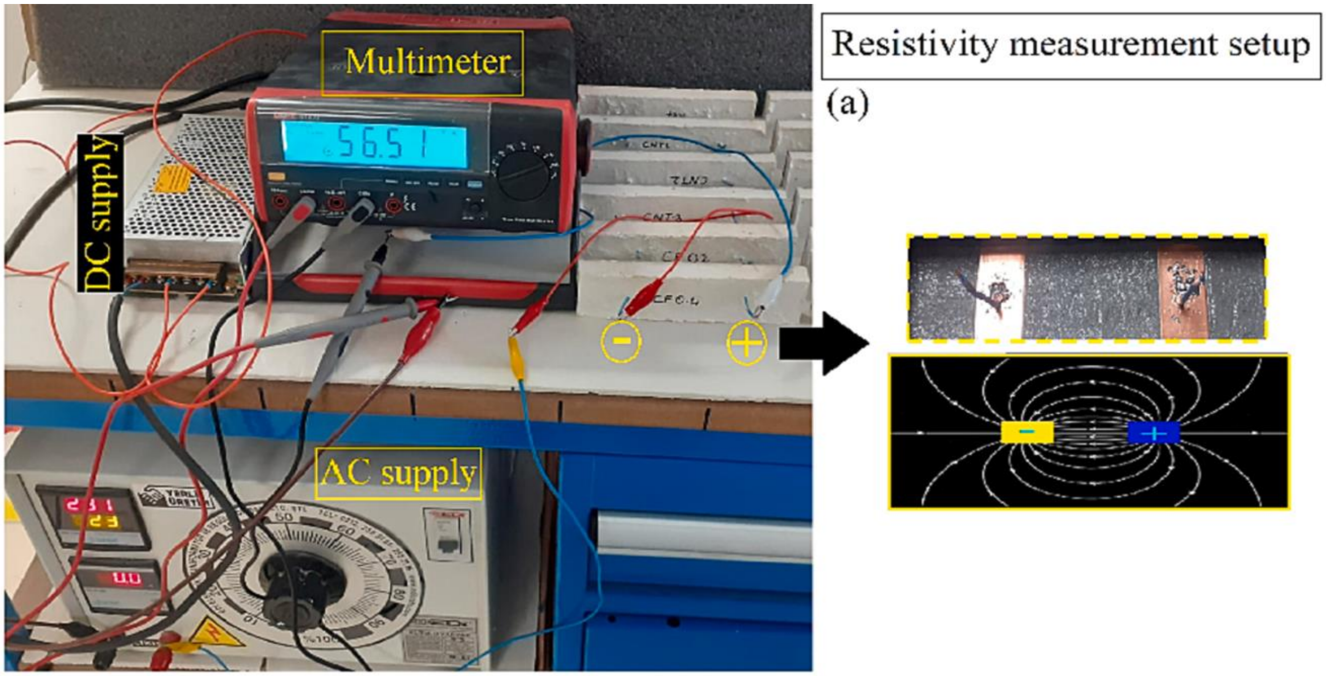

Figure 11. Test setup for resistivity measurement of electrically conductive concretes (Dehghanpour, 2023).

STRUCTURAL APPLICATIONS AND PRACTICAL IMPLEMENTATION

Structural elements

Geopolymer concrete (GPC) shows promise as a substitute for traditional Portland cement concrete (PCC) in structural elements including beams, slabs, and precast components. Research studies show that GPC achieves mechanical strength levels equal to or surpassing those of PCC while offering superior durability and better resistance to environmental degradation, including sulfate attack. The performance benefits of GPC stem from the dense aluminosilicate matrix that develops during geopolymerization processes (Jalal et al., 2024; Odeh et al., 2024). The precast construction industry successfully uses fly ash-based geopolymer formulations to produce structural components, including beams and railway sleepers. The controlled thermal curing process leads to fast polymerization of these mixtures, which produces quick strength development and fast hardening (Nawaz et al., 2020). The characteristics of GPC make it an ideal material for precast manufacturing because it enhances both production speed and structural performance. Studies about GPC slabs and beams show positive results regarding their load-bearing and flexural performance. The sustained loading behavior of GPC elements surpasses conventional concrete, while their fire resistance also improves (Unis Ahmed et al., 2022). The microstructure of GPC remains stable over time because of its low porosity and minimal shrinkage, which enhances both dimensional stability and structural integrity.

Field applications and commercial products

The market has seen an increase in documented field applications of geopolymer concrete through commercial products including bricks, blocks, railway sleepers, and precast beams (Ansari et al., 2025b). The use of industrial by-products such as fly ash and ground granulated blast furnace slag in GPC formulations supports sustainability goals by reducing CO2 emissions and promoting circular economy principles (Ansari et al., 2025b; Jalal et al., 2024). Ambient-cured GPC variants have been developed to suit practical construction conditions without the need for heat curing, broadening the scope of field applications (Nawaz et al., 2020; Odeh et al., 2024). These products have been employed in infrastructure projects, including road pavements and structural elements exposed to harsh environments, benefiting from GPC’s superior durability and chemical resistance (Nawaz et al., 2020). The cost-effectiveness of GPC products, despite higher initial material costs, is supported by their enhanced durability and reduced maintenance requirements over the lifecycle of structures (Ansari et al., 2025b; Odeh et al., 2024). This economic viability, combined with environmental benefits, positions GPC as a competitive alternative in commercial construction.

Standardization and regulatory issues

The promising performance of geopolymer concrete faces challenges due to standardization and regulatory frameworks for widespread adoption (Ansari et al., 2025b). The lack of standardized design specifications, curing protocols, and performance evaluation criteria creates uncertainty among practitioners and regulators when considering GPC for structural applications. Current research indicates that complete guidelines must be developed to address the differences in precursor materials, activator compositions, and curing conditions to achieve reliable quality and performance (Meskhi et al., 2023). The development of testing protocols and durability benchmarks continues to progress as researchers strive to align GPC standards with conventional concrete codes, while considering its distinct chemical properties and performance characteristics (Ansari et al., 2025b). The construction industry needs regulatory acceptance to expand GPC use, which necessitates collaboration between researchers, industry stakeholders, and standards organizations to establish strong certification processes (Ansari et al., 2025b). Addressing these issues will support the integration of GPC into current construction practices and promote its development for applications aimed at sustainability.

Economic viability and AI-based optimization of geopolymer concrete

Multiple research studies have evaluated the economic sustainability of geopolymer concrete (GPC) relative to Portland cement concrete by identifying both barriers and potential benefits. The research conducted by Martínez and Miller (2024) analyzed the life cycle assessment and production cost of GPC, which revealed that geopolymer concrete materials cost more than conventional concrete materials at the beginning of production. The material costs of a fly ash (FA) and ground granulated blast furnace slag (GGBS) blended geopolymer concrete (FA50%-GGBS50%) exceeded those of M25 grade conventional concrete by 27% when both concretes reached similar 28-day compressive strengths of 30 MPa for GPC and 33.45 MPa for OPC concrete. The high cost of alkaline activators such as sodium hydroxide and sodium silicate led to increased expenses that exceeded the cost savings from using industrial by-products, including fly ash and slag (Martínez & Miller, 2025). Rajini and Narasimha Rao (2020) presented a detailed economic analysis that demonstrated that GPC becomes more economical than OPC concrete when producing higher strength grades such as M50, by reducing costs by up to 11%. The material costs for M30 grade concrete were similar between GPC and OPC, with GPC being only 1.7% more expensive. The authors propose that GPC becomes more competitive in terms of cost as the strength grade increases because it allows for better supplementary cementitious material usage and enhanced mix design optimization (Rajini et al., 2020).

The elevated prices of GPC at present stem from industrial-scale production limitations and restricted activator supply networks according to Habert et al. (2011). The authors believe that geopolymer concrete systems will reduce their costs through better activator usage and improved supply chain management which will eventually make them less expensive than Portland cement concrete (Habert et al., 2011). The research conducted by Verma et al. (2022) and Martínez and Miller (2024) demonstrates that GPC concrete produces more than 50% lower greenhouse gas emissions than OPC concrete. The environmental advantages of GPC could lead to long-term economic benefits through carbon credit programs and regulatory incentives which improve its lifecycle cost-effectiveness (Martínez & Miller, 2025; Verma, Upreti, et al., 2022).

The intricate nature of GPC mix design has driven researchers to use artificial intelligence (AI) and machine learning (ML) techniques for modeling and optimizing its mechanical and rheological properties. The research by Rajini et al. (2025) used Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) and Gene Expression Programming (GEP) to achieve precise predictions of compressive strength and workability. The research on geopolymer concrete with agricultural waste materials (banana peel ash and sugarcane bagasse ash) showed that the ANFIS model performed better than ANN and GEP models with an R^2 of 0.998. AI models allow researchers to perform systematic investigations of mixed proportions and activator molarities and aggregate-to-binder ratios which result in optimized formulations that meet both mechanical performance requirements and sustainability goals (Rupwate & Kulkarni, 2025). The GEP method has proven successful in developing empirical strength prediction equations through large datasets that include extra water content and plasticizer dosage and curing conditions, and aggregate ratios. The AI models outperform traditional regression methods in accuracy and robustness, which provide engineers with efficient tools to modify geopolymer concrete mixes (Rajini et al., 2025; Rupwate & Kulkarni, 2025). The implementation of AI in geopolymer concrete research speeds up material development because it decreases the need for expensive and time-consuming experimental testing. The advancement of intelligent infrastructure becomes possible through predictive maintenance and performance optimization of GPC structures during their service life (Rajini et al., 2020).

Long-term performance and emerging research frontiers in geopolymer concrete

The scientific community now devotes more attention to studying the extended durability and operational performance of geopolymer concrete (GPC) because strength alone does not guarantee sustainable structural use. The research conducted by Vel et al. (2024) showed that using geopolymer aggregates instead of natural coarse aggregates leads to a 9%–15% increase in compressive strength while ultrasonic pulse velocity and rebound hammer tests verify the excellent quality of geopolymer aggregate concrete. The substitution results in higher porosity which causes sorptivity to increase by 10%–30% and chloride ingress to rise by the same amount thus potentially harming long-term durability. The strong bond between geopolymer aggregates and cement matrix improves their resistance to acid and sulfate attacks. The research demonstrates potential practical uses of geopolymer aggregate concrete in mass concreting and foundations and retaining walls and roads and dams and breakwater blocks but stresses the requirement for additional research to optimize porosity and chloride penetration for durability maintenance (Vel et al., 2024; Udhaya Kumar et al., 2024).

Wong (2022) conducted a review of geopolymer concrete's durability performance, demonstrating that this material shows outstanding resistance to heat, chloride penetration, acid attack, and abrasion. According to Wong, geopolymerization transforms various waste aluminosilicate materials into durable building materials that exhibit better chemical and physical properties than ordinary Portland cement (OPC) concrete. The research indicated that geopolymer concrete achieves its highest compressive strength when cured at optimal temperatures and times, but strength decreases when temperatures exceed 600 °C. The durability of geopolymer concrete improves with the addition of micro-silica and polypropylene fibers as additives. The abrasion resistance tests revealed that rubberized geopolymer concrete performed at least as well as OPC concrete, and wear depth decreased with increasing fiber content. Wong concluded that geopolymer concrete provides a durable substitute for OPC concrete in various construction projects (Wong, 2022; Wong, 2022).

The study by Revathi (2023) examined metakaolin (MK) and bottom ash (BA) blended geopolymer concrete under ambient curing conditions, demonstrating better resistance to sulfate and acid attacks than conventional concrete. The study showed that blended geopolymer concretes exhibit superior sorptivity, rapid chloride permeability, and water absorption properties, which contribute to improved durability in harsh environments (Revathi, 2023; Logesh Kumar & Revathi, 2023). The study by Karthi and Cibi (2024) on geopolymer concrete exposed to acidic environments demonstrated that aluminosilicate-based geopolymer binders outperform calcium silicate-based binders due to their structure lacking calcium and water. This review indicated that fly ash and GGBS-based geopolymer concretes maintain their strength better than OPC concrete after extended acid exposure. The strength of geopolymer concrete cubes decreased by 34% after 360 days of acetic acid immersion, whereas OPC concrete specimens lost 98% of their strength. Geopolymer concrete exhibits superior acid resistance, making it an ideal material for sewage pipes and structures subjected to acidic conditions (Karthi and Cibi, 2024). These researchers illustrate that geopolymer concrete develops outstanding long-term durability properties, including chemical resistance, thermal stability, and abrasion resistance, thereby rendering it suitable for sustainable infrastructure development. The use of geopolymer aggregates in concrete construction faces two main challenges: increased porosity and chloride penetration, which necessitate further research to optimize mix designs and validate laboratory results through field experiments. The complete utilization of geopolymer concrete in various structural applications relies on addressing these issues.

CONCLUSIONS

Geopolymer concrete functions as a sustainable alternative to traditional ordinary Portland cement (OPC) concrete by addressing environmental challenges stemming from high CO_2 emissions and natural resource exhaustion. The research uses a wide range of literature to analyze GPC's chemical foundations, raw material usage including industrial by-product such as fly ash, GGBFS, metakaolin and mix design optimization to enhance mechanical properties, and durability characteristics.

The superior performance of GPC strength results from the geopolymerization mechanism, which depends on complex aluminosilicate precursor and alkaline activator interactions. The mechanical and rheological properties of geopolymer composites have been improved through fiber reinforcement and nano-silica incorporation, and advanced curing regimes. The durability tests show that GPC demonstrates excellent resistance to sulfate attack and chloride ingress and acid exposure, and elevated temperatures, which makes it ideal for aggressive and infrastructure-intensive applications.

The research demonstrated the increasing number of studies about specific GPC formulations, which include fiber-reinforced systems, 3D-printable mortars and AI-optimized mix designs. The material demonstrates versatility through these developments, which show its ability to reduce carbon footprint while promoting circular economy practices through waste material without affecting its high strength and enduring durability needed for resilient infrastructure. Standardization efforts face obstacles because of material consistency issues between different precursor sources and the need to validate long-term performance under real-world conditions. To address these issues, future research needs to establish standardized protocols for precursor characterization and quality control while conducting extensive field studies to track durability and mechanical behavior. Advanced computational tools for optimized mix design should be integrated to enhance reproducibility and create properties that match specific applications. Future research needs to focus on conducting multi-scalar field studies while developing life-cycle assessments and creating global design codes to support broader adoption. The transition of geopolymer technology from innovative status to mainstream construction solution depends on the successful bridging of laboratory results with large-scale implementation.

DECLARATIONS

Competing interests

The author declares no competing interests in this research and publication.

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