

Revolutionizing Cementitious Materials: A Review on Fly ash and GGBS-based Geopolymer Applications

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Abstract—This paper examines the transformative potential of geopolymer technology in promoting sustainable construction by employing fly ash and ground granulated blast furnace slag as fundamental components in cementitious materials. Addressing the environmental challenges associated with Ordinary Portland Cement, particularly its significant CO₂ emissions, the study identifies geopolymers as an innovative solution to mitigate these impacts. Through the activation of fly ash and ground granulated blast furnace slag using alkaline solutions, geopolymers exhibit enhanced mechanical properties, environmental advantages, and improved durability under harsh conditions compared to Ordinary Portland Cement. The analysis highlights the critical roles of SiO₂ and Al₂O₃-rich precursors, precise activator ratios, and optimized curing regimes in achieving superior strength, reduced permeability, and thermal stability. The findings advocate for the broad adoption of fly ash and ground granulated blast furnace slag based geopolymers, positioning them as a crucial strategy for reducing the carbon footprint and advancing sustainable infrastructure development.

Keywords— Concrete, Fly ash, Ground granulated blast furnace slag, Thermal stability.

I. INTRODUCTION

Concrete, the most widely employed structural material on the planet, is favored due to the excellent availability of raw materials, ease of manufacturing processes, and its flexibility. Its primary binder, Ordinary Portland Cement (OPC), is now a significant environmental concern due to its enormous contribution to global CO₂ emissions. The future prospect of cement manufacturing signals a high growth rate of 4800 Mt by the year 2030 because the industry is already contributing approximately 7% of total CO₂ emissions [1]. As evident in Figure 1 given at the World Cement Association Conference (Oyak Cement), the global trend of cement manufacturing signals a growing demand from 1990 to the projected years up to 2030. The huge carbon footprint, coupled with high energy utilization and depletion of non-renewable raw materials, signals the imperative need for substitutes based on sustainability.

The geopolymer technology presents a new remedy to these issues by replacing the traditional Portland cement (OPC) with sustainable industrial waste by-product binders. In particular, fly ash (FA) and ground granulated blast furnace slag (GGBS) are emphasized due to their worldwide availability and natural pozzolanic properties. It is confirmed that FA and GGBS contain reactive elements such as silicon (Si), aluminum (Al), calcium (Ca), and others, as indicated in Table 1, thus validating their use as promising OPC alternatives [2].

The uncertainty of the chemical composition of these materials derived from various sources, however, presents a limitation to achieving consistent performance, thus necessitating precise material specifications and standardization of test procedures.

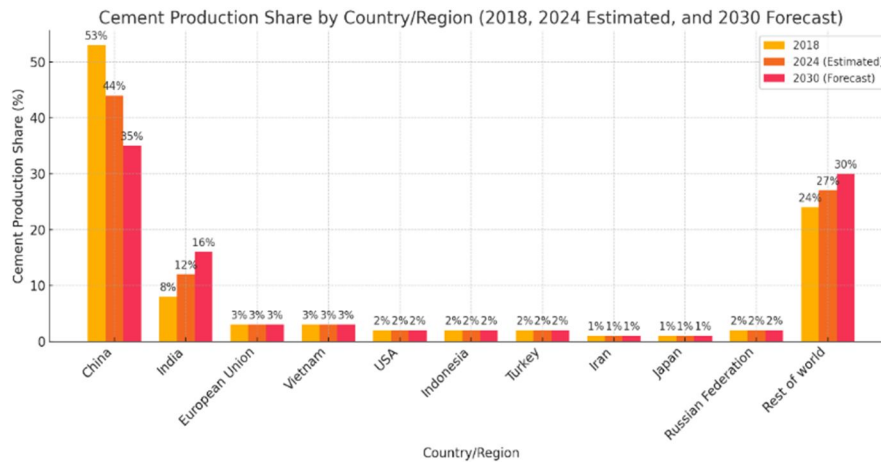


Figure 1. Worldwide Ordinary Portland Cement Production in 2018 and forecast for 2030

TABLE I. ELEMENTAL COMPOSITION OF ALTERNATIVE CEMENTITIOUS BINDERS

Chemical	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	Reference
FA	54.22	31.18	2.63	0.47	1.24	0.49	1.34	[3]
GGBS	37.5	6.4	0.51	8.6	34.6	0.38	-	[4]

Geopolymers, first conceived by Davidovits (2005) [5], are inorganic polymers prepared by activating aluminosilicate-rich materials using alkaline solutions. Geopolymer production compared to OPC bypasses the energy-intensive calcination step, lowering CO₂ emissions by approximately 80–85% relative to conventional cement [5,6]. Additionally, their use of industrial byproducts like rice husk ash and silica fume offer potential for further improvement of mechanical and environmental performance [7]. Industrial-scale geopolymer technology, however, poses serious challenges, such as the expense of alkaline activators, long-term durability of unknownness in different environmental conditions, and fewer field applications relative to OPC.

The utilitarian application of geopolymer technology goes beyond environmental aspects to other applications in infrastructure. For instance, FA and GGBS-based geopolymers are more resistant to chemical attack and possess enhanced thermal performance, thereby suitable for fire-resistant buildings and marine conditions [8]. In addition, advancements in 3D printing and materials science could potentially transform the production and personalization of geopolymer concretes, which would end scalability and design limitations [2].

From the environmental perspective, FA and GGBS addition to geopolymer blends not only reduces emissions but also keeps industrial waste out of landfills. Yet, the environmental impacts of the production of alkaline activators and the processing of possible toxic byproducts need to be researched more extensively to guarantee sustainable production systems [6]. Geopolymer concretes also provide a real mechanism for the realization of global net-zero emission levels, especially with the aid of novel carbon capture and storage technologies.

II. GEOPOLYMER TECHNOLOGY: EVOLUTION, MECHANISM, AND TERMINOLOGY

The introduction of geopolymer technology by Joseph Davidovits in 1991 [9] marked a pivotal advancement in the realm of sustainable construction materials. Coined "Geo-Polymer" from the concept of "geosynthesis," this innovation involves the creation of artificial rock at relatively low temperatures, typically below 100°C. The materials produced through this process exhibit remarkable hardness, durability, and thermal stability, making them a promising alternative to traditional Portland cement. Davidovits' pioneering research highlighted that amorphous substances rich in silicon (Si) and aluminum (Al) serve as optimal precursors for the production of geopolymers [10].

Geopolymer concrete, often referred to as inorganic polymer, alkali-activated cement, or mineral polymer, is widely recognized for its environmentally friendly and low-carbon attributes. Its multiple names, including alkali-bonded ceramic, hydroceramic, and alkali ash material, highlight the diversity in its synthesis processes and applications. Fundamentally, geopolymerization is a chemical reaction between aluminosilicate precursors

and alkaline activators, resulting in the formation of a three-dimensional aluminosilicate network with binding properties comparable to those of natural rock.

The conceptual model of geopolymerization, originally introduced by Glukhovskiy and later refined by researchers such as Nguyen Van Chanh and P. Duxson, describes a multi-phase strength development process, as depicted in Figure 2. This process begins with the dissolution of aluminosilicate materials in an alkaline solution, leading to the formation of gel phases, which subsequently solidify into a robust matrix. This mechanism underpins the high compressive strength, low permeability, and excellent chemical resistance of geopolymer concrete, making it a compelling alternative to traditional Portland cement [11]. By utilizing sustainable materials such as FA and GGBS, geopolymer technology addresses both environmental sustainability and the demand for high performance infrastructure development.

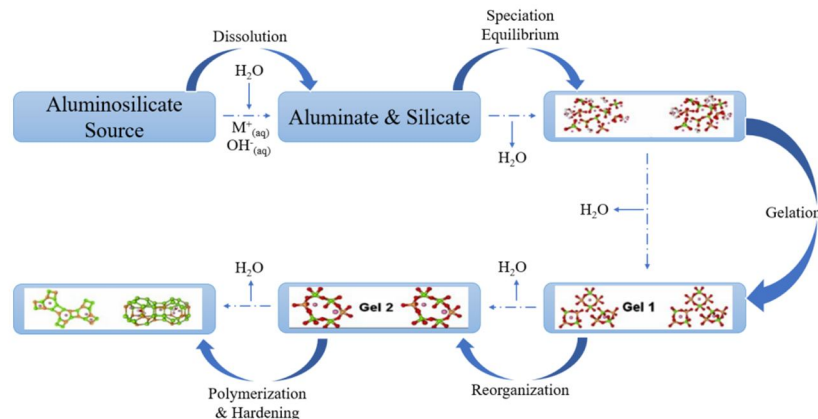


Figure 2: Geopolymerization Process Model

The transformation mechanism in geopolymerization begins with the dissolution of silicon (Si) and aluminum (Al) atoms from the source materials, facilitated by the action of alkaline activators. In this initial phase, Si and Al ions are separated and mobilized into the solution. The following stages, commonly referred to as the coagulation condensation phase, involve the transport, alignment, and condensation of these dissolved ions. During this process, Si, Al, and aluminosilicate molecules equilibrate within the solution, while rapid aluminosilicate dissolution and condensation reactions take place among adjacent hydroxyl (OH) ions. These reactions lead to the formation of oxygen bonds and the release of water molecules (H₂O), which typically remain trapped within the gel pores, contributing to the unique porous structure of the geopolymeric binder.

The resulting biphasic gel phase, consisting of an aluminosilicate binder and entrapped water, undergoes reorganization and rearrangement driven by thermodynamic and kinetic factors. These processes of molecular growth and crystal formation are critical in determining key physical properties such as compressive strength and durability of the final geopolymeric material. In the concluding stage, setting, polycondensation, and polymerization take place, typically catalyzed by mild heating (up to 90°C). This heating promotes the development of rigid chains or three-dimensional networks, referred to as N-A-S-H (sodium-aluminosilicate-hydrate) gel. As the temperature rises, water evaporates, and undissolved solid particles bond together, resulting in a crystalline geopolymeric structure. This entire transformation underscores the significance of thermodynamics, reaction kinetics, and the composition of raw materials in determining the performance and adaptability of geopolymer concrete for diverse applications.

A. Geopolymer concrete incorporating FA

Incorporating Alkaline Activators

Alkaline activators play a crucial role in the synthesis and performance of geopolymer concrete, significantly affecting both the reaction kinetics and the resulting mechanical properties. Research has shown that key factors such as the molarity of the alkali solution, the ratio of sodium silicate (Na₂SiO₃) to sodium hydroxide (NaOH), and the curing regime have a substantial impact on the compressive strength and durability of geopolymer concrete.

Hardjito et al. [12] studied the effects of varying NaOH molarities and the Na₂SiO₃/NaOH ratio, as illustrated in Figure 3. Their findings showed that a higher Na₂SiO₃/NaOH ratio (2.5) combined with an increased NaOH molarity (14M) significantly enhanced compressive strength, reaching 67.6 N/mm² after 7 days of curing at

60°C. This was markedly higher than the strength observed with a lower ratio (0.4) and 8M NaOH, which achieved 17.3 N/mm². Similarly, Palomo et al. [13] demonstrated that activators containing soluble silicates improved ash reactivity, resulting in geopolymer concrete with superior strength and a more compact microstructure compared to hydroxide-only solutions. The combination of NaOH and Na₂SiO₃ proved to deliver the highest compressive strength, highlighting the vital role of soluble silica in enhancing the polymerization process.

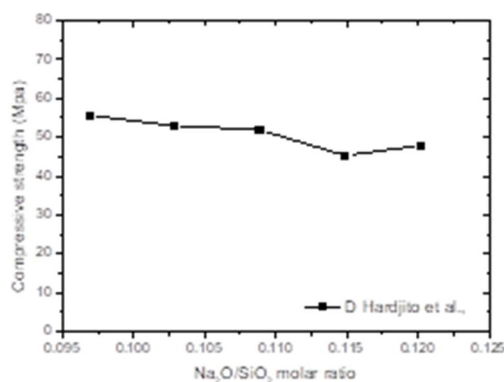


Figure 3. Effect of varying NaO₂-to-SiO₂ molar ratios on the compressive strength of materials

Temperature is another critical factor in optimizing the performance of alkaline activators. Palomo and Fernandez (Ángel Palomo) found that higher curing temperatures significantly accelerated the polymerization process, achieving compressive strengths exceeding 40 N/mm² within 10 hours at 115°C. However, they observed that extending the curing duration beyond 24 hours had minimal impact on further strength development, indicating an optimal window for thermal curing. Similarly, Nagalia et al. [11] demonstrated that FA with higher calcium oxide content, when activated with 14M NaOH, achieved compressive strengths of up to 43 N/mm². This enhancement was attributed to the formation of C-S-H (calcium silicate hydrate) gel, which improved the matrix's overall strength and durability.

The selection of alkali significantly impacts the economic viability of geopolymer production. Potassium-based activators like KOH offer mechanical properties comparable to sodium-based systems but come with a cost approximately 12% higher. This economic aspect is further supported by Qidwai et al., [15] who observed that increasing the NaOH molarity from 8M to 14M resulted in a notable enhancement in mechanical properties. Compressive strength improved from 11.14 N/mm² to 21.82 N/mm², while tensile strength increased from 1.66 N/mm² to 3.57 N/mm², demonstrating the performance gains associated with higher molarity sodium-based systems.

Dependent on the thermal profile and curing timeframe

Thermal conditions and curing duration play a pivotal role in determining the properties of geopolymer concrete, as supported by extensive research. Hardjito et al. [12] demonstrated that compressive strength increases significantly with curing temperatures up to 90°C. Using an 8M NaOH solution, specimens cured at 30°C, 45°C, 60°C, 75°C, and 90°C exhibited 7-day compressive strengths ranging from 34 N/mm² to 65 N/mm² (Figure 4(a)). With a higher NaOH concentration of 14M, the compressive strength further increased, ranging from 44 N/mm² to 72 N/mm² under the same conditions. However, strength gains were marginal beyond 60°C, and extending curing durations beyond 48–60 hours provided negligible additional benefits. These findings highlight optimal curing conditions for maximizing efficiency and performance.

While oven curing delivers higher early strengths, ambient curing presents a viable alternative in suitable environments. Samples cured at ambient temperatures of 18–25°C, 8–18°C, and 12–22°C achieved 7-day compressive strengths of 48 N/mm², 32 N/mm², and 44 N/mm², respectively, with gradual strength gains over 12 weeks reaching 58 N/mm², 38 N/mm², and 50 N/mm². This progressive strength development underscores the potential of ambient curing for energy-efficient applications. Supporting this, Rangan et al. [16] reported that geopolymer concrete cured at 60°C for 24 hours achieved compressive strengths of 55 N/mm² and 65 N/mm² at 7 and 28 days, respectively, while ambient-cured samples reached 47 N/mm² at 28 days. The naturally warm temperatures of tropical climates (around 30°C) make ambient curing particularly appealing, reducing dependence on external heat sources while achieving strength levels comparable to conventional OPC.

For large scale applications, the internal heat generated during polymerization can significantly enhance curing efficiency. Vaidya et al. [17] observed, as shown in Figure 4(b), that a 0.91-meter cube of geopolymer concrete maintained an internal temperature of approximately 42°C for five days due to exothermic reactions, resulting in compressive strengths of up to 43 N/mm². This highlights the potential for leveraging self-generated heat for curing in field applications. Elevated curing temperatures not only accelerate reaction kinetics but also enhance material properties. Chanh et al. [18] found that increasing curing temperatures from 40°C to 90°C reduced setting times and improved compressive strengths, with values ranging from 24 to 46 N/mm² depending on the temperature. Furthermore, Puertas et al. [19] demonstrated the synergistic effect of curing temperature and alkaline activator concentration. Samples cured at 25°C showed minimal strength gains after 28 days, while those cured at 65°C with a 10M NaOH solution achieved a compressive strength of 11 N/mm². These findings underscore the importance of tailoring curing conditions and activator concentrations to optimize polymerization and achieve desired structural performance.

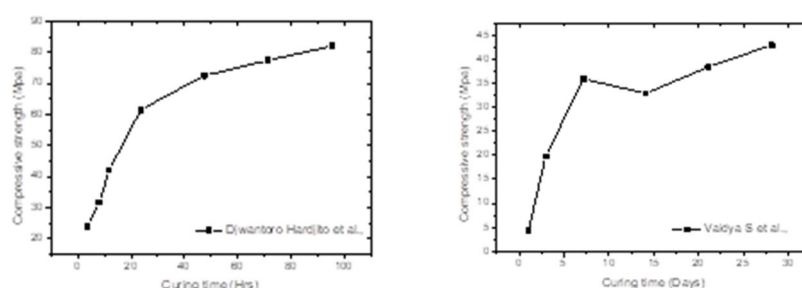


Figure 4. Investigating the impact of curing time on the mechanical strength of geopolymer concrete

Durability

Durability is a key factor influencing the long-term performance of FA based geopolymers, with numerous studies highlighting their remarkable resilience in harsh environmental conditions, positioning them as robust alternatives to conventional cementitious materials. Hardjito et al. [12,20], demonstrated the superior sulfate resistance of FA-based geopolymer concrete by immersing specimens in a 5% sodium sulfate (Na_2SO_4) solution for 52 weeks. The specimens exhibited minimal length change (0.015%), slight mass gain (1.5%), and no significant reduction in compressive strength (55–60 N/mm²). These findings were supported by Thokchom et al. (2009, 2010) [21,22], who reported that higher sodium oxide (Na_2O) content enhanced resistance against magnesium sulfate attack, with residual compressive strengths ranging from 50% to 90%, depending on activator concentrations. In comparative studies with Portland pozzolana cement (PPC), Sanni and Khadiranaikar (2012) [23] observed only a 12% loss in compressive strength for geopolymer concrete, compared to a 25% reduction for PPC (Figure 5). This improved performance was attributed to the absence of calcium compounds, which often lead to the formation of expansive calcium sulfates. Geopolymer concrete also demonstrated notable resilience under acidic conditions. Hardjito et al., [12] found that specimens exposed to 2% sulfuric acid (H_2SO_4) for 52 weeks retained significant residual strength, with surface deterioration confined to a depth of 20 mm. Observing less than 3% mass loss in geopolymer cubes immersed in 10% H_2SO_4 for 8 weeks. Similarly, Kolli and Potharaju (2015) [24] reported a 21% reduction in compressive strength for geopolymer concrete compared to a 44% loss for OPC, emphasizing the protective role of calcium-free aluminosilicate gels in mitigating acid-induced degradation.

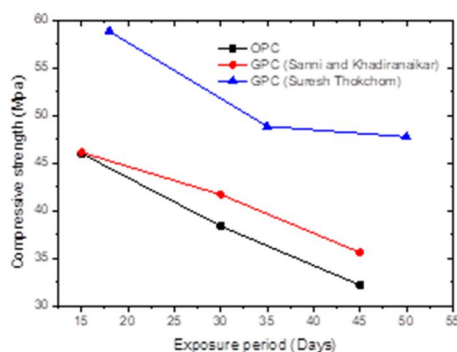


Figure 5. Compressive behavior of OPC and geopolymer mortars immersed in 10% sulfuric acid solution.

Thermal stability further enhances the durability of geopolymer materials. That potassium-activated geopolymers retained their microstructural integrity at temperatures exceeding 800°C, significantly outperforming sodium-activated variants and conventional concretes, which are more susceptible to thermal cracking. In marine and chloride-rich environments, Chanh et al. (2008)[18] reported that geopolymer mortar exposed to hydrochloric acid (HCl) showed only a 5% mass loss and minimal compressive strength reduction, underscoring its suitability for marine infrastructure. Kupwade and Allouche (2013) [25] reinforced these findings by showcasing reduced chloride diffusion coefficients, lower porosity, and minimal leaching in Class F FA-based geopolymer concrete subjected to cyclic wet-dry conditions in sodium chloride (NaCl) solution over 12 months, compared to OPC. These studies collectively emphasize the multi-dimensional durability of geopolymer materials, including superior resistance to sulfate and acid attacks, excellent thermal stability, and enhanced chloride impermeability. Such properties establish FA-based geopolymers as durable, sustainable alternatives to traditional cementitious systems. Their exceptional performance not only ensures long-term structural integrity but also addresses critical environmental challenges, positioning geopolymer technology as a key contributor to sustainable infrastructure development.

B. Geopolymer concrete incorporating GGBS

Chemical Arrangement and Fine Structure

The development of alkali-activated materials dates back to the pioneering work, the use of alkalis as cementitious activators by studying the setting behavior of ground slag with caustic potash solutions. This foundational research was expanded by Chassevent and Feret (1937) [26], who investigated the reactivity of slag with alkali solutions, including caustic soda and potash. Advanced field by examining clinker-free cement produced from slag activated with lime and caustic soda, laying a foundation for modern geopolymer technology [27]. By the 1970s, Glukhovsky identified the primary hydration products of alkali-activated slag as C-S-H and N-A-S-H gels, deepening the understanding of their chemical behavior. Building on this, Malone et al. outlined a stepwise gel formation process involving the dissolution of alkalis and source materials, the development of a Na_2SiO_3 layer on slag particles, the dissolution of alumina, the appearance of semi-crystalline C-S-H phases, and ultimately the formation of calcium aluminosilicate hydrate (C-A-S-H) gel within a crystalline, honeycomb-like matrix [4,28]. This structured mechanism underscores the importance of alkaline activators and reaction kinetics in forming durable gel phases. Research on ground granulated blast furnace slag (GGBS) has highlighted its high reactivity with minimal concentrations of alkaline activators [11]. The resulting C-A-S-H gel, which resembles the C-S-H gel in OPC hydration but with a lower Ca/Si ratio (0.9–1.2), exhibits superior chemical stability and durability. The type and concentration of the alkaline activator significantly influence reaction kinetics, with hydroxide-based systems producing a more ordered microstructure than silicate-based systems due to the availability of free silica in pore solutions [19]. GGBS solubility increases markedly at pH levels above 11, facilitating the dissolution of silica and alumina while polymerized silicates fill voids, resulting in a denser matrix and improved compressive strength. GGBS's thermal history, characterized by high amorphous content (~90%) and calcium oxide concentration (30–40%), promotes the formation of C-S-H gel over polysialate phases, even with low alkali concentrations (2–5%). This distinct chemical behavior makes GGBS an ideal precursor for geopolymer production. Additionally, the interfacial transition zone (ITZ) in alkali-activated GGBS often contains N-A-S-H gels, enhancing bonding and structural performance. These findings collectively confirm that the dense, crystalline matrix formed in alkali-activated systems provides high strength, low permeability, and exceptional durability. GGBS-based geopolymers emerge as a transformative solution for sustainable construction, aligning with the demands of modern infrastructure development.

Mechanical strength influenced by alkaline activators, curing temperature, and duration

The mechanical properties of geopolymer systems, especially those utilizing GGBS, are heavily influenced by the selection of alkaline activators, curing temperatures, and curing durations. Pu (1985) [11] demonstrated that GGBS-activated concrete achieved compressive strengths ranging from 60 to 80 N/mm², outperforming OPC in durability and bond strength. However, Wang (1991) [29] noted comparatively lower split tensile strength values, indicating a need for further optimization of activator compositions. Fernandez-Jimenez et al. (1999) [27] conducted a detailed statistical analysis, highlighting the critical role of activator type and concentration, curing temperature, and slag's specific surface area in strength development. Among the activators studied, sodium silicate (Na_2SiO_3) proved most effective, producing a 28-day compressive strength of 98 N/mm², whereas sodium carbonate (Na_2CO_3) was the least effective, yielding only 20 N/mm². Wang et al. (1994) [30] further identified a positive correlation between higher aluminum content in GGBS and enhanced compressive strength, with the optimal alkaline activator to GGBS ratio found to be between 0.38 and 0.45. Puertas et al. (2014) [19]

emphasized the influence of NaOH concentration and curing regimes, reporting that a 10M NaOH solution improved compressive strength to 52 N/mm² under ambient curing and 61 N/mm² with oven curing. However, challenges such as rapid setting and shrinkage-induced micro-cracking within the C-S-H gel were observed, highlighting the necessity for careful control of curing conditions to optimize performance and durability. Qidwai (2015) [15] also demonstrated a direct relationship between NaOH molarity and strength, with compressive strengths ranging from 22.62 N/mm² to 50.23 N/mm² as molarity increased from 8M to 14M. Cheng and Chiu (2003) [6] highlighted the synergistic effects of sodium silicate and metakaolin, reporting compressive strengths of 78 N/mm² when the SiO₂/Al₂O₃ ratio was optimized between 3.16 and 3.46. Similarly, Rajini and Rao (2014) achieved compressive strengths of 60.23 N/mm² and 65.23 N/mm² at 28 and 90 days, respectively. Palaniappan et al. (2013) [31] further demonstrated the superior performance of GGBS-based geopolymer concrete over OPC, with compressive and split tensile strengths improving by 13.82% and 18.23%, respectively. These studies collectively emphasize the critical roles of activator type, molarity, and curing conditions in optimizing the mechanical properties of geopolymer concrete.

C. Geopolymer concrete incorporating FA and GGBS

Mechanical Characteristics

The strength and microstructural properties of geopolymer concrete incorporating FA and GGBS have been extensively studied, highlighting critical relationships among GGBS content, alkaline activator concentration, curing conditions, and mechanical performance. Similarly, Bhikshma and Naveenkumar (2014) [2] demonstrated that higher GGBS content significantly enhanced compressive strength, achieving 71.07 N/mm² for 43% GGBS replacement. Krishnan et al. (2014) [26] observed peak compressive strengths of 80.5 N/mm² at 40% GGBS replacement under ambient curing, affirming the robust performance of GGBS-rich mixes without the need for oven curing. Microstructural analyses by Puertas et al. (2000)[19] revealed that increased GGBS content promotes the formation of C-S-H and C-A-S-H gels, which coexist with geopolymeric phases, bridging micropores and enhancing compactness. These collective findings demonstrate that incorporating GGBS into FA-based geopolymers enhances mechanical performance and microstructure through the synergistic formation of geopolymeric and calcium-based gels. This results in higher compressive strength, reduced permeability, and improved durability, establishing GGBS-based geopolymers as a sustainable and high-performance alternative to traditional cementitious materials.

Study of durability performance

The durability performance of geopolymer concrete incorporating FA and GGBS has been widely studied, demonstrating superior resistance to aggressive environments compared to conventional OPC concrete. Saavedra et al. (2016) [32] investigated geopolymer mortar with 20% FA and GGBS, activated using Na₂SiO₃ and NaOH solutions, and reported after 360 days of immersion in 5% Na₂SO₄ and MgSO₄ solutions that geopolymer concrete exhibited only a 33% strength loss in MgSO₄ while gaining 25% strength in Na₂SO₄. In contrast, OPC concrete suffered strength losses of 48% and 25%, respectively. Allahverdi and Skvara (2007) evaluated the acid resistance of geopolymer mortar containing 50% FA and GGBS under exposure to H₂SO₄ and HNO₃ solutions at pH values of 1, 2, and 3. They observed that geopolymer specimens exhibited lower corrosion than OPC at pH = 1, with performance converging at pH = 3. Rajamane et al. (2011, 2012) [33] further highlighted the excellent chloride resistance of geopolymer concrete through Rapid Chloride Permeability Tests (RCPT). For 100% GGBS-based geopolymer concrete, RCPT values of 722 coulombs were classified as "very low," while mixtures of 75% GGBS + 25% FA and 50% GGBS + 50% FA exhibited values of 888 and 1222 coulombs, respectively, significantly outperforming OPC concrete in chloride permeability. Additionally, the dense microstructure of geopolymer concrete, characterized by minimal permeability and enhanced bond strength, reduces susceptibility to chloride ingress and sulfate-induced deterioration. These properties underscore its durability and suitability for applications in harsh environments, positioning geopolymer concrete as a sustainable alternative to traditional cementitious systems.

III. APPLICATIONS AND PERFORMANCE BENEFITS OF GEOPOLYMER CONCRETE

Geopolymer concrete has emerged as a highly promising sustainable and high-performance alternative to OPC, primarily due to its distinctive mechanical properties, durability, and environmental advantages. By utilizing industrial by-products like FA and GGBS, geopolymer technology effectively tackles two critical challenges in modern construction: reducing carbon emissions and managing industrial waste. The incorporation of these materials not only alleviates environmental pollution from stockpiles but also lowers energy consumption and

production costs, positioning geopolymers as an economically and environmentally viable solution for sustainable infrastructure development.

One of the key advantages of geopolymer concrete is its superior mechanical performance. Geopolymer mixtures could achieve compressive strengths of 25–30 MPa within 24 hours without requiring specialized curing regimes, showcasing their self-curing capability and rapid early strength development. This makes geopolymer concrete particularly suitable for time-sensitive applications such as airport runway repairs, road rehabilitation, and emergency structural interventions, where high strength and quick setting are essential. Moreover, the stress-strain behavior of geopolymer concrete, although influenced by the choice of source materials and activators, has been found to closely resemble that of OPC-based systems, ensuring seamless adaptability for structural applications.

Geopolymer concrete demonstrates exceptional durability in aggressive environments, attributed to its low permeability and dense microstructure, which enhance resistance to sulfate and acid attacks. This makes it particularly well-suited for applications such as sewer systems, wastewater treatment plants, marine structures, and coastal infrastructure. Research by Duxon et al. (2007) and Torres-Carrasco and Puertas (2017) [19,28,31] also highlights its excellent resistance to thermal degradation and abrasion, enabling its use in refractory concrete, industrial flooring, chimneys, and fire-resistant structures. These durability attributes allow geopolymer concrete to significantly outperform OPC in environments prone to chemical aggression, high temperatures, and mechanical wear, ensuring an extended service life and reduced maintenance costs.

The versatility of geopolymer concrete is evident through its wide range of applications in civil engineering and industrial sectors. Real-world case studies have highlighted its robustness and reliability in both structural and non-structural uses. For example, reinforced geopolymer concrete box culverts manufactured and tested in Perth, Australia, successfully met stringent performance standards for structural applications (Rangan, 2014). Similarly, precast bridge decks and retaining wall panels showcased exceptional strength and durability, further demonstrating the material's suitability for critical infrastructure projects (Aldred and Day, 2012) [34]. In sewer systems, precast geopolymer pipes exposed to aggressive environments exhibited superior durability compared to traditional OPC pipes, validating their effectiveness for wastewater management systems (Lloyd and Rangan, 2010) [16].

The successful application of geopolymer technology in large-scale construction projects highlights its structural viability and practical feasibility. A notable example is the Global Change Institute (GCI) building at the University of Queensland, Australia, a pioneering structure featuring cement-less construction, as illustrated in Figure 6 (James Aldred) [34]. This four-story building incorporates geopolymer concrete precast panels of M40 grade, demonstrating the material's ability to meet modern architectural and engineering standards. Furthermore, the extensive use of geopolymer concrete for pathways in Australia and New Zealand has shown exceptional durability and reliable performance under diverse climatic conditions, bolstering confidence in its suitability for infrastructure exposed to environmental stresses (Rangan, 2014) [35].



Figure 6. Showcasing sustainable building design, the Global Change Institute will lead by example

Beyond civil engineering, geopolymer concrete has demonstrated exceptional effectiveness in extreme environments where conventional materials are inadequate. One significant application is the stabilization and encapsulation of hazardous and radioactive wastes. At the Kam-Kotia mining area in Canada, geopolymer binders successfully immobilized toxic substances such as arsenic, mercury, and lead within a durable concrete matrix, effectively preventing their leaching into the environment (Davidovits et al., 1990) [9]. Similarly, at the Wismut mine water treatment facility in Dresden, geopolymer technology was utilized to solidify uranium and

radium-contaminated sludge, providing a safe and long-lasting containment solution. These cases underscore the potential of geopolymer concrete to address critical environmental remediation challenges, particularly in contaminated industrial and mining sites.

Furthermore, Geopolymer concrete's rapid setting properties and high early strength make it particularly well-suited for rehabilitation and repair applications. In Houston, Texas, a 49-meter-long sewer pipe with a 1.5-meter diameter was successfully rehabilitated using fiber-reinforced geopolymer mortar, achieving a final strength of 55 MPa, as illustrated in Figure 7 (Matthews) [36]. This project demonstrated the material's effectiveness in extending the lifespan of aging infrastructure, even under chemically aggressive conditions. Additionally, its exceptional thermal resistance and low shrinkage have made it an ideal choice for refractory applications such as chimneys, fireplaces, and fire-resistant components, where reliable performance under extreme temperatures is critical.



Figure 7. A study of the sewer pipe condition: prior to and following rehabilitation

Source: (Matthews, J.; Selvakumar, A.; Vaidya, S.; Condit, W., 2015)[36]

Despite its many advantages, geopolymer concrete faces several challenges that warrant further research and development. Variability in the composition of source materials, such as FA and GGBS, can result in performance inconsistencies. The handling and application of alkaline activators, which are essential for the geopolymerization process, pose practical difficulties, particularly in on-site construction scenarios. Additional concerns include issues like efflorescence, increased drying shrinkage, and the formation of secondary by-products under dry conditions, all of which can affect long-term performance reliability. However, ongoing advancements in material formulation, standardization, and the creation of admixtures specifically designed for geopolymer systems offer promising pathways to address these challenges, paving the way for broader adoption of geopolymer concrete in construction.

IV. CONCLUSION

The study underscores the transformative potential of geopolymer technology, utilizing fly ash and ground granulated blast furnace slag as sustainable alternatives to Ordinary Portland Cement. By harnessing these abundant industrial by-products, this approach significantly reduces carbon emissions while addressing the environmental challenges associated with Ordinary Portland Cement production. Geopolymers, activated by optimized alkaline solutions, demonstrate superior mechanical properties, exceptional durability, and resilience in aggressive environments, establishing them as eco-friendly and high-performance construction materials. The research highlights the critical influence of precursor composition, activator ratios, and curing conditions on achieving optimal geopolymerization. These factors contribute to reduced permeability, thermal stability, and long-term structural integrity. Despite challenges such as material variability and efflorescence, advancements in formulation techniques and standardization offer promising solutions for wider adoption. This study emphasizes the pivotal role of geopolymer concrete in modern infrastructure development, seamlessly aligning ecological objectives with sustainable construction practices.

REFERENCES

- [1] H. Sverdrup, D. Koca, K.V. Ragnarsdottir, Investigating the sustainability of the global silver supply, reserves, stocks in society and market price using different approaches, *Resour. Conserv. Recycl.* 83 (2014) 121–140. <https://doi.org/10.1016/j.resconrec.2013.12.008>.

- [2] I. Navarrete, F. Vargas, P. Martinez, A. Paul, M. Lopez, Flue gas desulfurization (FGD) fly ash as a sustainable, safe alternative for cement-based materials, *J. Clean. Prod.* 283 (2021) 124646. <https://doi.org/https://doi.org/10.1016/j.jclepro.2020.124646>.
- [3] A. Karimipour, J. de Brito, Influence of polypropylene fibres and silica fume on the mechanical and fracture properties of ultra-high-performance geopolymer concrete, *Constr. Build. Mater.* 283 (2021) 122753. <https://doi.org/10.1016/j.conbuildmat.2021.122753>.
- [4] Y. Liu, C. Shi, Z. Zhang, N. Li, D. Shi, Mechanical and fracture properties of ultra-high performance geopolymer concrete: Effects of steel fiber and silica fume, *Cem. Concr. Compos.* 112 (2020) 103665. <https://doi.org/10.1016/j.cemconcomp.2020.103665>.
- [5] J. Davidovits, Geopolymer chemistry and sustainable development. The Poly(sialate) terminology: a very useful and simple model for the promotion and understanding of green-chemistry., *Geopolymer 2005 Conf.* (2005) 9–16.
- [6] J. Zhao, L. Tong, B. Li, T. Chen, C. Wang, G. Yang, Y. Zheng, Eco-friendly geopolymer materials: A review of performance improvement, potential application and sustainability assessment, *J. Clean. Prod.* 307 (2021) 127085. <https://doi.org/10.1016/j.jclepro.2021.127085>.
- [7] L. Vickers, A. van Riessen, W.D.A. Rickard, Precursors and Additives for Geopolymer Synthesis, *SpringerBriefs Mater.* (2015) 17–37. https://doi.org/10.1007/978-981-287-311-8_2.
- [8] S.S. Shaikh, A. Patil, Recycling Of Ggbs into Geopolymer Concrete and Creating Eco-Friendly Cement Product, 2 (2020) 304–311. <https://doi.org/10.35629/5252-0203304311>.
- [9] J. Davidovits, Geopolymers: Inorganic Polymeric New Materials, *J. Therm. Anal. Calorim.* 37 (1991) 1633–1656. <https://doi.org/10.1007/BF01912193>.
- [10] Prof. Dr. Joseph Davidovits, Environmentally Driven Geopolymer Cement Applications, *Geopolymer 2002 Conf.* (2002) 1–9.
- [11] A. Palomo, M.T. Blanco-Varela, M.L. Granizo, F. Puertas, T. Vazquez, M.W. Grutzeck, Chemical stability of cementitious materials based on metakaolin, 1999.
- [12] D. Hardjito, S.E. Wallah, D.M.J. Sumajouw, B. V Rangan, Fly Ash-Based Geopolymer Concrete, *Aust. J. Struct. Eng.* 6 (2005) 77–86. <https://doi.org/10.1080/13287982.2005.11464946>.
- [13] A. Palomo, M.W. Grutzeck, M.T. Blanco, Alkali-activated fly ashes: A cement for the future, *Cem. Concr. Res.* 29 (1999) 1323–1329. [https://doi.org/10.1016/S0008-8846\(98\)00243-9](https://doi.org/10.1016/S0008-8846(98)00243-9).
- [14] G. Nagalia, Y. Park, A. Abolmaali, P. Aswath, Compressive Strength and Microstructural Properties of Fly Ash–Based Geopolymer Concrete, *J. Mater. Civ. Eng.* 28 (2016). [https://doi.org/10.1061/\(asce\)mt.1943-5533.0001656](https://doi.org/10.1061/(asce)mt.1943-5533.0001656).
- [15] J. Shang, J.G. Dai, T.J. Zhao, S.Y. Guo, P. Zhang, B. Mu, Alternation of traditional cement mortars using fly ash-based geopolymer mortars modified by slag, *J. Clean. Prod.* 203 (2018) 746–756. <https://doi.org/10.1016/j.jclepro.2018.08.255>.
- [16] B. V Rangan, B.V. Rangan, P. Fieaust, C. Faci, FLY ASH-BASED GEOPOLYMER CONCRETE, 2008.
- [17] S. Vaidya, E.I. Diaz, E.N. Allouche, Experimental Evaluation of Self-Cure Geopolymer Concrete for Mass Pour Applications, n.d. <http://www.flyash.info/>.
- [18] N. Van Chanh, -Assoc Professor, B. Dang Trung, D.M. Van Tuan-Candidate, RECENT RESEARCH GEOPOLYMER CONCRETE, 2008.
- [19] F. Puertas, S. Martõ Áñez-Ramõ Áñez, S. Alonso, T. Va Ázquez, Alkali-activated fly ash/slag cement Strength behaviour and hydration products, n.d.
- [20] D. Hardjito, ACI Materials, 2004. <https://www.researchgate.net/publication/303836414>.
- [21] S. Thokchom, P. Ghosh, S. Ghosh, RESISTANCE OF FLY ASH BASED GEOPOLYMER MORTARS IN SULFURIC ACID, 2009. www.arpnjournals.com.
- [22] S. Thokchom, P. Ghosh, S. Ghosh, Performance of Fly ash Based Geopolymer Mortars in Sulphate Solution Engineering Science and Technology Review, 2010. www.jestr.org.
- [23] S.H. Sanni, -Asst Professor, Performance of geopolymer concrete under severe environmental conditions, *Int. J. Civ. Struct. Eng.* 3 (2012). <https://doi.org/10.6088/ijcser.201203013037>.
- [24] P. Malasani, Indian Concrete Institute Journal : Performance characteristics of Geopolymer concrete in Acid and Sulphate Environment, 2016. <https://www.researchgate.net/publication/293401740>.
- [25] K. Kupwade-Patil, E.N. Allouche, P. Eng. Examination of Chloride-Induced Corrosion in Reinforced Geopolymer Concretes, (2013). [https://doi.org/10.1061/\(ASCE\)MT.1943](https://doi.org/10.1061/(ASCE)MT.1943).
- [26] J. Mishra, B. Nanda, S.K. Patro, R.S. Krishna, A comprehensive review on compressive strength and microstructure properties of GGBS-based geopolymer binder systems, *Constr. Build. Mater.* 417 (2024). <https://doi.org/10.1016/j.conbuildmat.2024.135242>.
- [27] A. Palomo, A. Fernández-Jiménez, Alkaline activation, procedure for transforming fly ash into new materials. Part I: Applications, n.d. <http://www.flyash.info/>.
- [28] P. Duxson, A. Fernández-Jiménez, J.L. Provis, G.C. Lukey, A. Palomo, J.S.J. Van Deventer, Geopolymer technology: The current state of the art, *J. Mater. Sci.* 42 (2007) 2917–2933. <https://doi.org/10.1007/s10853-006-0637-z>.
- [29] J. Wang, J. Xie, C. Wang, J. Zhao, F. Liu, C. Fang, Study on the optimum initial curing condition for fly ash and GGBS based geopolymer recycled aggregate concrete, *Constr. Build. Mater.* 247 (2020). <https://doi.org/10.1016/j.conbuildmat.2020.118540>.

- [30] D. Wu, J. Wang, T. Miao, K. Chen, Z. Zhang, Performance Optimization of FA-GGBS Geopolymer Based on Response Surface Methodology, *Polymers (Basel)*. 15 (2023). <https://doi.org/10.3390/polym15081881>.
- [31] A. Fernández-Jiménez, A.G. de la Torre, A. Palomo, G. López-Olmo, M.M. Alonso, M.A.G. Aranda, Quantitative determination of phases in the alkaline activation of fly ash. Part II: Degree of reaction, *Fuel* 85 (2006) 1960–1969. <https://doi.org/10.1016/j.fuel.2006.04.006>.
- [32] V. Arularasi, P. Thamilselvi, S. Avudaiappan, E.I.S. Flores, M. Amran, R. Fediuk, N. Vatin, M. Karelina, Rheological behavior and strength characteristics of cement paste and mortar with fly ash and GGBS admixtures, *Sustain.* 13 (2021). <https://doi.org/10.3390/su13179600>.
- [33] G. Thakur, Y. Singh, R. Singh, C. Prakash, K.K. Saxena, A. Pramanik, A. Basak, S. Subramaniam, Development of GGBS-Based Geopolymer Concrete Incorporated with Polypropylene Fibers as Sustainable Materials, *Sustain.* 14 (2022). <https://doi.org/10.3390/su141710639>.
- [34] J. Aldred, J. Day, IS GEOPOLYMER CONCRETE A SUITABLE ALTERNATIVE TO TRADITIONAL CONCRETE?, n.d.
- [35] R. Anuradha, V. Sreevidya, R. Venkatasubramani, B. V Rangan, MODIFIED GUIDELINES FOR GEOPOLYMER CONCRETE MIX DESIGN USING INDIAN STANDARD, 2012. www.SID.ir.
- [36] J. Matthews, A.M. Asce, A. Selvakumar, S. Vaidya, W. Condit, Large-Diameter Sewer Rehabilitation Using a Spray-Applied Fiber-Reinforced Geopolymer Mortar, (2014). [https://doi.org/10.1061/\(ASCE\)](https://doi.org/10.1061/(ASCE)).