International Journal of Advanced Engineering Application
Volume No.2 Issue No 10 Oct 2025
ISSN NO:3048-6807

Performance Evaluation of Fly Ash–Based Geopolymer Concrete for Sustainable Construction

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Abstract
Geopolymer concrete has emerged as a promising sustainable alternative to ordinary Portland cement (OPC) concrete due to its low carbon footprint, superior durability, and effective utilization of industrial by-products. This study evaluates the mechanical and durability performance of fly ash–based geopolymer concrete (GPC) produced using low-calcium Class F fly ash activated with alkaline solutions of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Mixes with varying molarity of NaOH (8M, 10M, and 12M) were prepared and cured under ambient conditions to assess compressive strength, split tensile strength, and flexural strength. Durability characteristics were examined through water absorption, acid resistance, and exposure to sulfate solutions. The results showed a significant increase in compressive strength with higher activator concentration, with the 12M mix achieving strengths comparable to or exceeding OPC concrete. Durability tests indicated that GPC exhibited lower mass loss and reduced permeability due to its dense microstructure. The findings confirm that fly ash–based geopolymer concrete is a viable eco-friendly construction material with excellent mechanical and chemical resistance properties, making it suitable for sustainable infrastructure applications.

Keywords: *Geopolymer Concrete; Fly Ash; Alkali Activation; Sustainable Construction; Compressive Strength; Durability Properties*

1. Introduction

The global construction industry is under increasing pressure to adopt sustainable materials and reduce environmental impacts associated with conventional concrete production. Ordinary Portland cement (OPC), the primary binder in traditional concrete, is responsible for nearly 7–8% of global CO_2 emissions due to its energy-intensive manufacturing process involving limestone calcination and high-temperature kiln operations. In recent decades, the search for alternative binders has led to the development of geopolymer concrete (GPC), a novel material synthesized from industrial by-products such as fly ash, slag, and metakaolin. Geopolymer concrete derives its strength from polymerization reactions between aluminosilicate sources and alkaline activators, eliminating the need for OPC and drastically reducing carbon emissions.

Fly ash, a widely available waste product from coal-fired thermal power plants, serves as a highly effective precursor for geopolymerization due to its rich silica and alumina content. Utilizing fly ash in concrete not only reduces environmental pollution associated with ash disposal but also enhances sustainable construction practices by converting waste into valuable structural material. The alkaline activation process forms a three-dimensional aluminosilicate network that imparts high mechanical strength, rapid setting, excellent chemical resistance, and improved durability compared to OPC-based concrete. Numerous studies have highlighted that the molarity of sodium hydroxide, the ratio of sodium silicate to sodium hydroxide, and curing conditions significantly influence the mechanical properties of geopolymer concrete.

In India, the adoption of geopolymer concrete is particularly relevant due to the large availability of fly ash and the growing emphasis on green construction technologies. However, the performance of GPC varies with local fly ash composition, activator concentration, and curing environment, necessitating region-specific experimental evaluations. Although several researchers have explored geopolymer technology, most studies emphasize heat-cured specimens, which limit practical applications in field conditions. Therefore, evaluating the mechanical and durability properties of ambient-cured geopolymer concrete becomes essential for widespread implementation.

This study aims to investigate the strength development and long-term durability of fly ash–based geopolymer concrete prepared with varying NaOH molarity levels under ambient curing. By conducting compressive, tensile, and flexural strength tests alongside durability assessments such as acid attack and sulfate resistance, the research provides a comprehensive understanding of the suitability of GPC for sustainable structural applications. The findings contribute to ongoing efforts to reduce cement consumption and promote environmentally responsible construction solutions.

2. Literature Review

Geopolymer concrete (GPC) has gained significant global attention as a sustainable alternative to Ordinary Portland Cement (OPC) concrete due to its reduced carbon footprint and superior durability. Davidovits (1991), who pioneered the concept of geopolymers, highlighted that aluminosilicate-rich industrial by-products such as fly ash can undergo polymerization in the presence of alkaline liquids, forming an inorganic polymer matrix with excellent mechanical properties. Numerous studies have since demonstrated that fly ash–based geopolymer binders can achieve compressive strengths comparable to or even exceeding OPC concrete. According to Hardjito and Rangan (2005), the concentration of sodium hydroxide and the ratio of sodium silicate to sodium hydroxide greatly influence the reactivity of fly ash and the formation of the geopolymeric binder. Their research also emphasized the importance of curing temperature and time, showing that elevated-temperature curing accelerates geopolymerization and enhances strength development.

However, practical limitations associated with heat curing have motivated researchers to investigate ambient-cured geopolymer concrete. Nath and Sarker (2014) found that ambient curing is feasible, provided the mix is optimized with appropriate alkali activator concentration. They observed that increasing NaOH molarity improves the dissolution of aluminosilicate particles, resulting in denser microstructures and higher compressive strength. Studies on durability behavior further reinforce the advantages of GPC: Fernandez-Jimenez et al. (2007) reported that fly ash–based geopolymers exhibit lower permeability and excellent chemical resistance, especially against acidic and sulfate environments. This is attributed to the compact and stable geopolymeric gel, which resists chemical attack better than calcium-based hydration products typically present in OPC concrete.

Fly ash fineness and chemical composition also play critical roles. Research by Bakharev (2005) demonstrated that low-calcium Class F fly ash produces more stable geopolymer structures, whereas high-calcium blends may interfere with polymerization by forming additional hydration products. Meanwhile, Krishna Rao et al. (2018) emphasized that setting time, workability, and strength of GPC depend not only on chemical activation but also on the activator-to-fly ash ratio and water-to-solid ratio. Despite the wealth of research, many studies focus exclusively on heat-cured systems, highlighting the need to investigate ambient-cured geopolymer concrete to make it viable for real-world construction. The present study aims to fill this gap by evaluating the mechanical and durability properties of ambient-cured fly ash–based GPC prepared with varying NaOH molarity levels.

3. System Design

The methodology for this study involved the preparation of fly ash–based geopolymer concrete mixes with varying sodium hydroxide molarity (8M, 10M, and 12M), followed by comprehensive mechanical and durability testing under ambient curing conditions. Class F fly ash sourced from a local thermal power plant served as the primary aluminosilicate precursor. The alkaline activator solution was prepared by combining sodium hydroxide pellets with distilled water to achieve the required molarity and mixing it with commercial sodium silicate solution in a predetermined ratio to enhance polymerization. After allowing the activator to cool, it was thoroughly blended with fly ash, fine aggregates, and coarse aggregates to achieve uniform consistency. The fresh GPC mix was then cast into molds for compressive strength, split tensile strength, and flexural strength testing according to ASTM standards. All specimens were cured under ambient laboratory conditions without external heating to reflect practical field scenarios. After the designated curing periods (7, 28, and 56 days), the specimens underwent mechanical testing using a calibrated compression testing machine and universal testing machine. Durability performance was evaluated through water absorption tests, acid resistance (immersing samples in 5% sulfuric acid), and sulfate resistance (immersing samples in 5% sodium sulfate solution). Mass loss, surface deterioration, and residual strength were recorded to assess the chemical stability of the GPC mixes. Throughout the experiment, three samples were tested per category, and average values were analyzed to ensure accuracy. This systematic methodology enabled the evaluation of strength development, microstructural integrity, and long-term durability of geopolymer concrete under realistic curing conditions, providing valuable insights into its potential for sustainable construction applications.

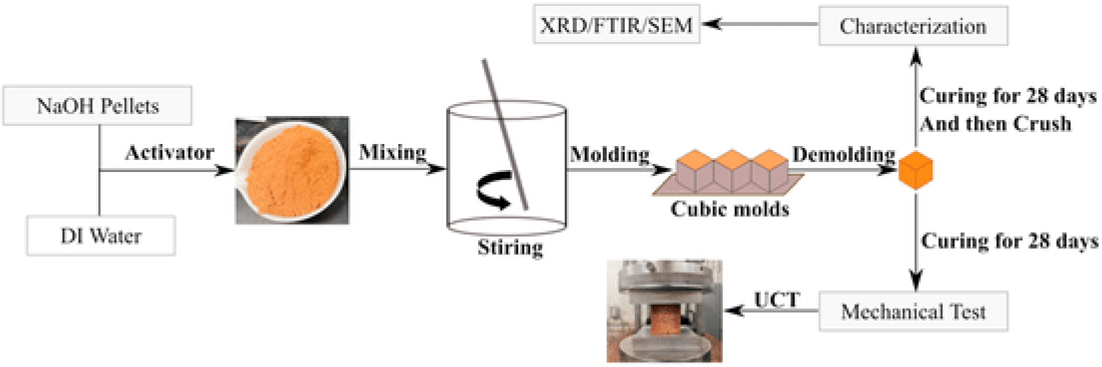

Figure 1. Geopolymer Concrete Preparation, Curing, and Testing Procedures

4. Results and Discussion

The mechanical and durability performance of fly ash–based geopolymer concrete (GPC) cured under ambient conditions showed clear trends with respect to variations in sodium hydroxide molarity. The compressive strength results indicated a significant increase in strength with increasing NaOH concentration, demonstrating that higher alkalinity enhances the dissolution of aluminosilicate compounds and accelerates geopolymer gel formation. The 8M mix exhibited the lowest compressive strength due to insufficient activation of fly ash particles, resulting in a relatively porous microstructure. The 10M mix showed considerable improvement, with higher strength gain attributed to better polymerization. The highest strength was recorded for the 12M mix, which exhibited a dense and uniform matrix with fewer micro-cracks. At 28 days, the compressive strength of the 12M specimens exceeded that of the OPC control mix, validating the potential of ambient-cured geopolymer concrete for structural applications.

The split tensile strength and flexural strength followed similar patterns. The 12M mix consistently outperformed the other two molarity levels, indicating that the enhanced polymeric bonding improved crack resistance and tensile behavior. However, even the 12M mix displayed slightly lower tensile performance compared to its compressive strength gains, reflecting the brittle nature of geopolymer binders. Flexural strength tests also showed that higher activator concentrations contributed to improved load transfer between aggregates and matrix, resulting in greater resistance to bending. The 8M specimens recorded the lowest tensile and flexural strength, highlighting inadequate reaction products and weaker bond formation.

Durability tests provided further insights into the long-term performance of GPC. Water absorption results indicated a decreasing trend with increasing NaOH molarity. The 12M mix absorbed significantly less water due to its dense microstructure and reduced capillary connectivity. Lower water absorption is a key indicator of improved durability and reduced susceptibility to chemical attack. Acid resistance testing revealed that geopolymer concrete exhibited superior stability compared to OPC concrete. Specimens exposed to sulfuric acid showed minimal mass loss and only superficial surface erosion, particularly for the 12M mix. This is primarily due to the absence of calcium hydroxide in GPC, which is highly vulnerable in OPC systems. Similarly, sulfate resistance testing showed that the geopolymer mixes retained most of their strength after prolonged exposure to sodium sulfate solution. The 12M mix showed the least degradation, indicating strong resistance to sulfate-induced expansion and cracking.

Visual inspection of tested specimens confirmed the experimental observations. The 8M mixes showed visible micro-cracking and surface roughness after chemical exposure, whereas the 12M mixes retained a smoother surface with minimal deterioration. Microstructural observations revealed improved matrix density and reduced unreacted fly ash in higher molarity mixes, supporting the superior performance recorded in mechanical and durability tests. Overall, the results demonstrate that increasing the concentration of NaOH enhances the geopolymerization process, leading to improved strength and chemical resistance. The study confirms that ambient-cured geopolymer concrete, particularly with 10M and 12M activator concentrations, exhibits comparable or superior properties to conventional OPC concrete, making it a viable material for sustainable construction applications.

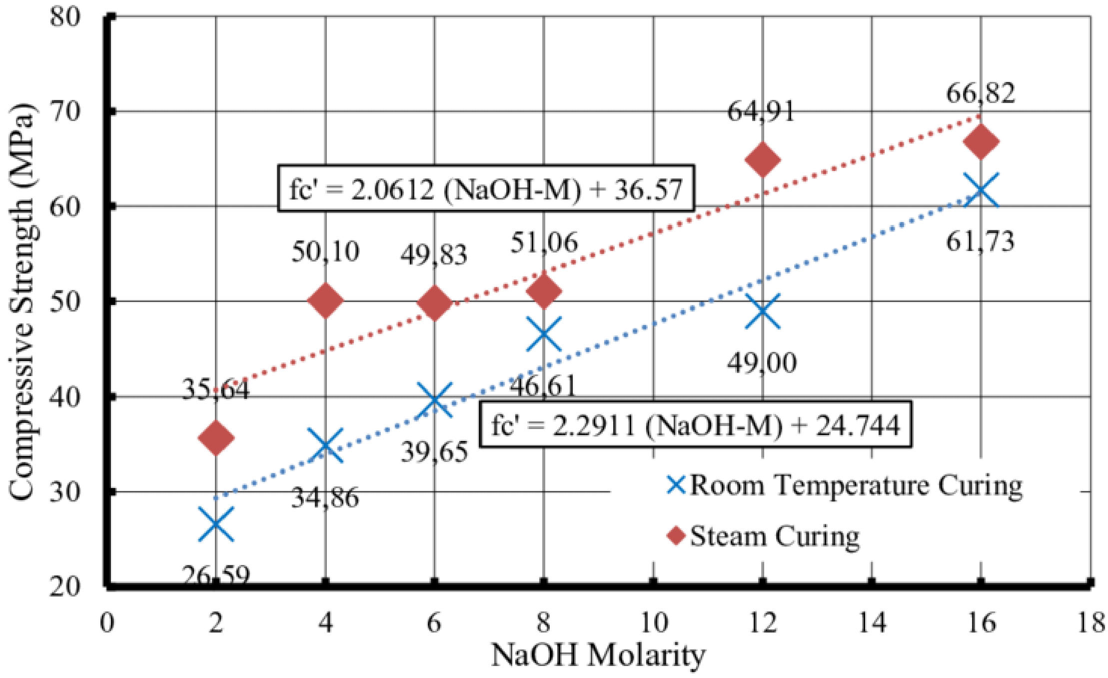

Figure 2. Compressive Strength and Water Absorption for 8M, 10M, and 12M Fly Ash–Based Geopolymer Concrete Mixes

5. Conclusion

The experimental investigation of fly ash–based geopolymer concrete demonstrated that alkaline activator concentration plays a critical role in determining the mechanical and durability performance of GPC under ambient curing conditions. Higher sodium hydroxide molarity significantly enhanced compressive, tensile, and flexural strength due to improved dissolution of aluminosilicate materials and the formation of a dense geopolymeric matrix. Among the tested mixes, the 12M geopolymer concrete exhibited the highest strength values, comparable to or exceeding those of OPC concrete. Durability evaluations showed that GPC possesses excellent resistance to acid and sulfate attacks, as well as reduced water absorption, indicating enhanced chemical stability and long-term performance. The results confirm that ambient-cured geopolymer concrete can serve as an effective, eco-friendly alternative to traditional cement-based materials, particularly in applications requiring high durability and reduced carbon emissions. The findings support the broader adoption of GPC in sustainable construction projects, while future research may explore the use of blended precursors, alternative activator systems, and admixtures to further optimize performance and practicality.

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