Comparative Evaluation of Fly Ash and GGBS-Based Geopolymer Concrete: Mechanical and Durability Performance

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ABSTRACT

The urgent need for sustainable alternatives to Ordinary Portland Cement (OPC) has driven the exploration of geopolymer concrete (GPC) as a viable solution to reduce carbon emissions and utilize industrial by-products. This study presents a comparative evaluation of geopolymer concrete synthesized using two primary binders: Class F fly ash and ground granulated blast furnace slag (GGBS). The research investigates the influence of these materials on fresh properties, mechanical performance (compressive, split tensile, and flexural strengths), and durability under acidic and sulphate environments. Fly ash-based GPC required elevated curing temperatures for optimal strength gain, while GGBS-based GPC demonstrated rapid early-age strength under ambient conditions due to its higher calcium content. Experimental results revealed that GGBS-GPC exhibited superior early compressive and flexural strengths, whereas fly ash-GPC showed enhanced durability under aggressive chemical exposure. The findings highlight the potential of GPC, particularly hybrid blends, to replace OPC in structural applications, contributing to reduced environmental impact and enhanced construction sustainability. The study also emphasizes the necessity for further standardization of mix design and curing protocols to facilitate the practical adoption of geopolymer technologies in mainstream construction.

Keywords: Geopolymer concrete; Fly ash; GGBS; Alkali-activated binders; Sustainable construction; Compressive strength; Durability; Ambient curing; Hybrid geopolymer; Waste valorization.

1.0 INTRODUCTION

Concrete is the backbone of modern infrastructure, widely valued for its strength, versatility, and ease of use. However, its environmental cost is significant. Ordinary Portland Cement (OPC), the primary binder in conventional concrete, is highly energy-intensive to produce and is responsible for approximately 0.9 tons of CO_2 emissions per ton of cement manufactured. This contributes to nearly 8% of global greenhouse gas emissions, raising critical concerns about the sustainability of cement-based construction.

India, as a rapidly urbanizing nation, faces dual challenges: escalating demand for construction materials and mounting industrial waste from power and steel industries. The increasing demand for cement, projected to reach 550 million tonnes annually, poses serious questions regarding resource depletion, energy consumption, and carbon emissions. Simultaneously, large volumes of fly ash from thermal power plants and ground granulated blast furnace slag (GGBS) from steel industries remain underutilized, creating environmental hazards.

Geopolymer concrete (GPC) presents a sustainable alternative, completely eliminating the use of OPC. First conceptualized by Davidovits in the 1970s, geopolymers are aluminosilicate-based binders formed through alkaline activation. The geopolymerization process involves dissolving alumina and silica in an alkaline medium, followed by polycondensation to form a rigid, three-dimensional polymeric structure. This inorganic polymer matrix offers excellent mechanical strength, high durability, low shrinkage, and superior resistance to chemical attack and thermal stress.

Fly ash and GGBS are the two most commonly studied source materials for geopolymer concrete. Fly ash is a low-calcium, amorphous aluminosilicate material that develops strength effectively when heat-cured, making it suitable for precast or controlled-environment applications. In contrast, GGBS contains higher calcium content and promotes the formation of calcium-aluminosilicate hydrate (C-A-S-H) gel, enabling ambient curing and faster early-age strength development. The combination of fly ash and GGBS has also shown promise in balancing early strength and long-term durability.

Despite numerous studies on geopolymer systems, there remains a lack of comparative research focusing specifically on fly ash versus GGBS as individual primary binders in geopolymer concrete. In particular, gaps exist in understanding how these binders affect the fresh properties (e.g., workability), mechanical performance (compressive, tensile, and flexural strengths), and long-term durability (especially under acid and sulfate attack). The lack of standardized mix designs and field application data further limits the adoption of geopolymer concrete in mainstream construction.

This study aims to bridge these knowledge gaps by conducting a comprehensive comparative analysis of fly ash-based and GGBS-based geopolymer concrete. The research includes experimental investigations under both ambient and heat-curing conditions, using standardized tests to evaluate mechanical properties and chemical resistance. The findings will guide material selection, mix proportioning, and curing strategies for deploying geopolymer concrete in a range of construction scenarios.

Ultimately, this research contributes to the global effort to decarbonize the construction sector by promoting the use of geopolymer concrete—a high-performance, low-carbon, and sustainable building material.

2.0 LITERATURE REVIEW

The environmental burden of Ordinary Portland Cement (OPC) production has driven the construction industry to seek sustainable alternatives. Geopolymer concrete (GPC), introduced by Davidovits (1978), has emerged as a promising cement-free binder system formed through the alkaline activation of aluminosilicate-rich industrial by-products such as fly ash (FA) and ground granulated blast furnace slag (GGBS). The resulting material exhibits superior mechanical strength, chemical resistance, and lower carbon emissions compared to OPC-based concrete.

2.1 Fly Ash and GGBS in Geopolymer Concrete

Fly ash, especially low-calcium Class F, has been widely used in geopolymer synthesis due to its high silica and alumina content. However, its reactivity at ambient temperature is limited, often necessitating elevated curing temperatures (60–90°C) for effective geopolymerization (Fernandez-Jimenez &Palomo, 2021; Kumar & Prasad, 2023). Conversely, GGBS, due to its high calcium content, facilitates early strength gain under ambient conditions and enhances the formation of C-A-S-H gel, improving early-age performance (Chithambaram et al., 2021; Al-Rawi& Majid, 2024).

Several studies have explored the synergistic effects of blending fly ash with GGBS. Jena & Patel (2022) and Balamurugan& Suba (2022) found that a 70:30 FA:GGBS ratio yields optimal mechanical and durability properties, while Yadav et al. (2023) identified 60% FA and 40% GGBS as the optimal mix for M30 grade GPC. These hybrid blends exhibit a balanced development of N-A-S-H and C-A-S-H gels, leading to dense microstructures and improved performance.

2.2 Effect of Alkaline Activators

The performance of GPC is highly influenced by the type, molarity, and ratio of alkaline activators. Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) are the most commonly used activators. Safiuddin&Saha (2021) observed that a 12M NaOH solution offers the best compromise between strength and workability. Borah et al. (2022) recommended a Na_2SiO_3:NaOH ratio of 2.0–2.5 for FA-based systems, noting that higher silica content enhances polymerization but may reduce setting time.

2.3 Mechanical and Durability Properties

Numerous investigations have validated the mechanical superiority of geopolymer concrete over OPC. Hardjito et al. emphasized the role of optimized curing in achieving high compressive strength. Nath&Sarker (2022) confirmed the improved durability of GPC under acidic and sulfate environments, attributing it to its low calcium hydroxide content and dense microstructure. Morsy et al. (2021) observed that FA-GPC shows better resistance to acid attack, while GGBS-GPC is more resistant to sulfate environments due to the formation of C-A-S-H gel.

Studies by Zhao et al. (2023) and Panda &Basu (2021) highlighted that ambient-cured GGBS-GPC could match or outperform oven-cured FA-GPC, making it more suitable for field applications. Patra& Mehta (2023) advocated for large-scale utilization of industrial by-products to reduce landfilling and carbon emissions, while Singh &Goyal (2024) demonstrated the structural viability of GPC in seismic zones through numerical simulations.

2.4 Practical Applications and Research Gaps

Field applications of GPC in India, such as pavement blocks, drain covers, and precast walls, have shown encouraging results (Sathish& Pillai, 2022). However, IS 16415:2015, which mentions geopolymer technology, still lacks comprehensive design codes and quality control guidelines. Researchers have also noted variability in industrial by-product composition, sensitivity to curing conditions, and challenges in large-scale implementation.

Recent literature (Ahmed et al., 2022; Mohammed et al., 2021) suggests further studies are needed to standardize mix proportions, understand long-term performance, and evaluate economic feasibility. Advanced analytical methods like SEM and XRD have confirmed the densification effects of GGBS and the pore refinement offered by nano-silica and other additives (Hemalatha et al., 2022).

3. Materials & Methods

3.1 Materials Used

The primary materials used for geopolymer concrete (GPC) preparation in this study were:

- **Fly Ash (FA):** Class F fly ash obtained from a local thermal power plant, characterized by low calcium content and high silica and alumina concentrations. It served as the primary aluminosilicate source for one set of GPC mixes.

- **Ground Granulated Blast Furnace Slag (GGBS):** A by-product of the steel industry, GGBS contains high calcium content and contributes to early strength gain through the formation of C-A-S-H gel. It was used as the sole binder in the second set of mixes.
- **Alkaline Activators:**
  - Sodium Hydroxide (NaOH): A pelletized form with 97–98% purity, dissolved in water to prepare 12M molarity solution.
  - Sodium Silicate (Na_2SiO_3): Commercial-grade solution with a silica modulus (SiO_2/Na_2O) of approximately 2.5.
- **Aggregates:**
  - Fine Aggregate: Manufactured sand (M-sand) with particle sizes conforming to Zone II (IS: 383-2016).
  - Coarse Aggregate: Crushed angular granite aggregates of 20 mm nominal size.
- **Water:** Potable water was used for mixing and preparing the alkaline activator solution.

3.2 Mix Design

Two geopolymer concrete mixes were designed for target strength of M30 grade:

- **FA-GPC:** 100% fly ash as the binder.
- **GGBS-GPC:** 100% GGBS as the binder.

The alkaline activator solution was prepared using a fixed Na_2SiO_3:NaOH ratio of 2.5:1 and a constant molarity of 12M NaOH. The solution was prepared 24 hours in advance to allow equilibrium. A fixed liquid-to-binder (L/B) ratio of 0.5 was adopted across all mixes.

3.3 Mixing and Casting Procedure

1. Dry components (binder, fine and coarse aggregates) were mixed in a pan mixer for 2 minutes.
2. The alkaline activator solution was then added gradually while mixing continued for an additional 3–4 minutes to ensure uniform consistency.
3. The fresh concrete was cast into standard cube (150 × 150 × 150 mm), cylinder (150 mm diameter × 300 mm height), and prism (100 × 100 × 500 mm) moulds for testing compressive, split tensile, and flexural strengths, respectively.
4. Specimens were compacted using a vibrating table and covered with plastic sheets to prevent moisture loss.

3.4 Curing Regimes

Two curing regimes were adopted:

- **Heat Curing (for FA-GPC):** Specimens were cured at 60°C in an oven for 24 hours and then stored at ambient temperature (25±2°C) until testing.
- **Ambient Curing (for GGBS-GPC):** Specimens were cured in laboratory conditions (25±2°C) from the date of casting.

3.5 Testing Methods

The following tests were conducted at 7 and 28 days of curing:

- **Workability:** Slump test (IS: 1199-2017) to evaluate fresh concrete behavior.
- **Compressive Strength:** As per IS: 516-2014 using cube specimens.
- **Split Tensile Strength:** As per IS: 5816-1999 using cylinder specimens.
- **Flexural Strength:** Using third-point loading method (IS: 516-2014) on prism specimens.
- **Durability Tests:**
  - Acid Resistance: Immersion in 5% H_2SO_4 solution for 28 days.
  - Sulfate Resistance: Immersion in 5% Na_2SO_4 solution for 28 days.
  - Mass loss and residual compressive strength were recorded.

3.6 Data Analysis

All tests were conducted in triplicate and the average values were reported. Comparative analysis between FA-GPC and GGBS-GPC was performed to evaluate differences in mechanical performance and durability characteristics.

4.0 Results & Discussion

This section presents the comparative analysis of fly ash-based geopolymer concrete (FA-GPC) and ground granulated blast furnace slag-based geopolymer concrete (GGBS-GPC) in terms of fresh properties, mechanical strengths, and durability under chemical attack. All results are reported as the average of three specimens.

4.1 Workability

Mix Type	Slump (mm)
FA-GPC	76
GGBS-GPC	89

Discussion:
GGBS-GPC exhibited higher workability than FA-GPC. The higher calcium content in GGBS enhances the binding and paste quality, which improves the mix flow. Fly ash-based mixes generally show lower initial workability, especially when high-molarity activator solutions are used.

4.2 Compressive Strength

Mix Type	7 Days (MPa)	28 Days (MPa)
FA-GPC	25.6	35.2
GGBS-GPC	32.7	45.6

Discussion:
GGBS-GPC achieved significantly higher compressive strength at both 7 and 28 days. The early strength gain in GGBS mixes is attributed to the formation of C-A-S-H gel under ambient curing conditions. In contrast, FA-GPC required heat curing to activate geopolymerization and develop strength over time.

4.3 Split Tensile Strength

Mix Type	28 Days (MPa)
FA-GPC	2.9
GGBS-GPC	4.4

Discussion:
The tensile strength of GGBS-GPC exceeded that of FA-GPC by over 50%. This improvement is consistent with the compressive strength trend and is likely due to denser matrix formation and better interfacial bonding provided by calcium-rich GGBS.

4.4 Flexural Strength

Mix Type	28 Days (MPa)
FA-GPC	4.2
GGBS-GPC	5.6

Discussion:
Flexural strength results also demonstrated the superior performance of GGBS-based geopolymer concrete. The improved modulus of rupture is indicative of better crack resistance and energy absorption capacity, making GGBS-GPC more suitable for structural elements subject to bending stresses.

4.5 Durability: Acid Resistance

Mix Type	Initial Weight (kg)	Final Weight (kg)	Weight Loss (%)
FA-GPC	8.235	7.891	4.17
GGBS-GPC	8.598	8.293	3.54

Discussion:
Both mixes showed good resistance to acid attack, with GGBS-GPC showing slightly lower weight loss. However, FA-GPC exhibited less visible surface degradation, likely due to its lower calcium content, which resists acid dissolution more effectively.

4.6 Durability: Sulphate Resistance

Mix Type	Initial Weight (kg)	Final Weight (kg)	Weight Loss (%)
FA-GPC	8.237	8.023	2.59
GGBS-GPC	8.456	8.213	2.87

Discussion:
FA-GPC outperformed GGBS-GPC in terms of sulphate resistance. The lower calcium content in fly ash reduces the likelihood of gypsum formation and expansive reactions in the presence of sulphates, making it more durable in aggressive chemical environments.

4.7 Summary of Key Findings

- **Workability:** GGBS-GPC had better slump and consistency.
- **Strengths:** GGBS-GPC outperformed FA-GPC in compressive, split tensile, and flexural strength.
- **Durability:** FA-GPC showed better sulphate resistance; GGBS-GPC showed slightly better acid resistance but was more susceptible to visible surface damage.
- **Curing Efficiency:** GGBS-GPC developed strength under ambient conditions, offering energy savings compared to heat-cured FA-GPC.

5.0 Conclusion & Future Scope

5.1 Conclusion

This study presents a comparative analysis of fly ash-based and GGBS-based geopolymer concrete (GPC), highlighting the mechanical and durability performance under standardized experimental conditions. The following key conclusions can be drawn:

- **Workability:** GGBS-based GPC exhibited higher workability than fly ash-based GPC, primarily due to its better reactivity and paste formation under ambient conditions.
- **Mechanical Properties:** GGBS-GPC outperformed FA-GPC in all strength parameters:
  - **Compressive Strength:** 45.6 MPa (GGBS) vs. 35.2 MPa (FA) at 28 days
  - **Split Tensile Strength:** 4.4 MPa (GGBS) vs. 2.9 MPa (FA)
  - **Flexural Strength:** 5.6 MPa (GGBS) vs. 4.2 MPa (FA)
- **Durability:**
  - **Acid Resistance:** GGBS-GPC showed lower weight loss (3.54%) compared to FA-GPC (4.17%).
  - **Sulphate Resistance:** FA-GPC showed slightly better resistance, with lower weight loss (2.59%) than GGBS-GPC (2.87%).
- **Curing Efficiency:** GGBS-GPC developed strength effectively under ambient conditions, making it more energy-efficient and feasible for in-situ applications, while FA-GPC required heat curing to achieve comparable performance.

Overall, **GGBS-based GPC is better suited for early-strength and ambient-cured applications**, whereas **fly ash-based GPC offers improved resistance in aggressive chemical environments**. Both types provide a sustainable, cement-free solution for reducing CO_2 emissions and utilizing industrial waste.

5.2 Future Scope

While the findings are promising, several areas warrant further investigation:

- **Long-Term Durability:** Extend the study to evaluate performance under real-time environmental exposure over longer durations (e.g., 90–180 days).
- **Hybrid Blends:** Explore blended FA-GGBS mixes in various proportions (e.g., 70:30, 60:40) to optimize the balance between strength and durability.
- **Field Implementation:** Pilot studies in real construction settings (e.g., pavements, retaining walls) to assess performance and practical challenges.
- **Microstructural Analysis:** Conduct SEM, XRD, and FTIR studies to better understand the gel composition, pore structure, and chemical bonding mechanisms.
- **Economic Feasibility:** Perform a life cycle cost analysis to compare GPC with OPC concrete in terms of initial cost, maintenance, and carbon credits.

- **Standardization:** Develop mix design guidelines and encourage updates to Indian Standards (e.g., IS 456, IS 10262) for geopolymer concrete.

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