A Comparative Study on Geopolymer Concrete Using Fly Ash and GGBS

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ABSTRACT

The environmental concerns associated with the high carbon footprint of Ordinary Portland Cement (OPC) have intensified research into alternative, sustainable construction materials. Geopolymer concrete (GPC), synthesized from industrial by-products such as fly ash (FA) and ground granulated blast furnace slag (GGBS), has emerged as a promising eco-friendly alternative binder system. This review paper provides a comprehensive comparative analysis of FA-based, GGBS-based, and blended FA-GGBS geopolymer concretes, focusing on their mechanical properties, durability, microstructural characteristics, curing conditions, and sustainability. The analysis highlights that while FA-based systems demonstrate superior long-term performance, they often require elevated temperature curing. In contrast, GGBS-based geopolymers provide high early strength and ambient curing capabilities. Blended systems offer a balanced performance profile, combining the advantages of both precursors. Additionally, the review discusses the influence of key parameters such as activator concentration, precursor ratio, curing method, and the use of additives. The findings emphasize the need for mix design optimization and standardized practices to enable the large-scale implementation of geopolymer concrete as a sustainable construction material.

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

1.0 INTRODUCTION

The construction industry is undergoing a paradigm shift towards sustainability due to the environmental consequences associated with the production of Ordinary Portland Cement (OPC). Cement manufacturing contributes approximately 7–8% of global CO_2 emissions, primarily through the calcination of limestone and high energy consumption. In response, **geopolymer concrete (GPC)** has emerged as a promising eco-friendly alternative binder system, attracting growing attention for its potential to significantly reduce the carbon footprint of concrete without compromising mechanical performance or durability.

Geopolymers are inorganic alumino-silicate materials formed by the activation of industrial by-products, such as **fly ash (FA)** and **ground granulated blast furnace slag (GGBS)**, using alkaline solutions. These alumino-silicate precursors not only utilize waste streams efficiently but also contribute to the production of concrete with high early strength, excellent chemical resistance, and enhanced thermal stability. Among the various source materials, **low-calcium fly ash (Class F)** and **high-calcium GGBS** have been extensively studied due to their global availability, reactivity, and compatibility in blended systems.

Fly ash-based geopolymer concrete exhibits desirable long-term mechanical and durability properties under heat curing conditions; however, it often suffers from slow setting and strength development at ambient temperatures. On the other hand, GGBS-based or FA-GGBS blended geopolymers offer improved early-age strength, setting characteristics, and ambient curing feasibility owing to the presence of calcium, which promotes the formation of additional C–A–S–H type gels alongside N–A–S–H gels. The interaction between these binders significantly affects the microstructural evolution, strength gain, shrinkage behavior, and long-term durability of the composite.

Despite the individual and combined use of FA and GGBS being well-researched, a comprehensive understanding of their **comparative performance** in geopolymer concrete systems—covering mechanical behavior, mix design optimization, curing strategies, microstructural attributes, and durability under different exposures—is still evolving. Additionally, various factors such as activator concentration, curing method, FA/GGBS ratio, and inclusion of nano-materials further influence the behavior of GPC and merit detailed investigation.

This review aims to critically analyze and compare the performance of **fly ash-based**, **GGBS-based**, and **blended FA-GGBS geopolymer concretes**, drawing insights from experimental studies, microstructural analyses, and durability evaluations. Emphasis is placed on identifying key material parameters, synthesis approaches, and property correlations to guide future mix design and practical implementation of geopolymer concrete as a sustainable construction material.

The rapid pace of industrialization and urbanization has significantly increased the demand for construction materials, especially concrete, which remains the most widely used man-made material globally. However, the conventional concrete production process is highly unsustainable, primarily due to the heavy reliance on Ordinary Portland Cement (OPC), which contributes to nearly **8% of global carbon dioxide (CO_2) emissions**. This pressing environmental challenge has spurred global research efforts to identify sustainable and durable alternatives to OPC, paving the way for the development of **geopolymer concrete (GPC)** — a low-carbon, cement-free binder system derived from industrial by-products.

Geopolymer concrete is synthesized through the **alkaline activation of aluminosilicate-rich materials**, notably **fly ash (FA)** and **ground granulated blast furnace slag (GGBS)**. These materials, abundantly available as waste from coal-fired power plants and steel industries, respectively, not only help divert industrial waste from landfills but also offer significant environmental advantages by reducing the energy intensity and emissions associated with traditional cement-based concrete. In this context, GPC is not merely a material innovation but a strategic step towards sustainable infrastructure development.

Among the various geopolymer systems, **fly ash-based geopolymer concrete** has been extensively studied due to its widespread availability, fine particle size, and high reactivity under heat curing. It is particularly rich in silica and alumina, which promotes the formation of a three-dimensional sodium aluminosilicate hydrate (N–A–S–H) gel, contributing to long-term strength and durability. However, FA-based geopolymers typically require elevated curing temperatures (60–80°C) for optimal performance, limiting their applicability in ambient environments and on-site casting.

In contrast, **GGBS-based geopolymer concrete**, either used alone or in combination with FA, introduces a **calcium-rich phase** that reacts with the alkaline solution to form calcium silicate hydrate (C–S–H) and calcium aluminosilicate hydrate (C–A–S–H) gels. These additional reaction products significantly accelerate the setting process, enhance early-age strength development, and improve ambient curing characteristics. This makes **FA-GGBS blends** a highly practical solution for large-scale field applications, combining the workability and durability of FA with the strength-enhancing features of GGBS.

A number of studies have explored the **synergistic interaction between FA and GGBS** in hybrid geopolymer systems, revealing improvements in compressive strength, chloride and sulfate resistance, reduced drying shrinkage, and superior thermal stability. However, the performance of these materials varies significantly based on key influencing factors such as:

- **Type and fineness of precursors**
- **FA/GGBS blend ratio**
- **Type and concentration of alkaline activator (NaOH, Na_2SiO_3, KOH, etc.)**
- **Curing temperature and duration**
- **Water-to-binder ratio and molarity**
- **Use of additives such as nano-silica, metakaolin, and fibers**

Despite the increasing volume of experimental research, **a consolidated comparative understanding of fly ash vs. GGBS-based geopolymer concrete** — including their behavior under mechanical, chemical, thermal, and environmental stressors — remains fragmented across literature. As such, there is a critical need to synthesize and evaluate this body of work to provide clear guidelines for selecting the optimal binder type for specific applications in structural and infrastructure projects.

This review paper aims to address that gap by systematically comparing the **mechanical properties, workability, microstructural characteristics, durability performance, and sustainability aspects** of fly ash-based, GGBS-based, and blended geopolymer concretes. It draws upon over two decades of research findings to highlight the advantages and limitations of each binder system under various curing regimes and mix proportions. In doing so, the paper seeks to inform researchers, engineers, and practitioners about the potential, challenges, and practical considerations for adopting geopolymer technology in modern concrete construction.

2.0 LITERATURE REVIEW

The growing focus on sustainable construction has accelerated research into alternative binder systems for concrete. Among these, **geopolymer concrete (GPC)**—developed from industrial by-products such as **fly ash (FA)** and **ground granulated blast furnace slag (GGBS)**—has emerged as a potential substitute for conventional cement-based concrete. Extensive studies have investigated the individual and combined effects of these precursors on the mechanical performance, durability, and microstructural evolution of geopolymer composites.

2.1 Fly Ash-Based Geopolymer Concrete

Fly ash, especially low-calcium (Class F) fly ash, has been the primary source material in early geopolymer research due to its rich aluminosilicate content. The seminal work by **Hardjito and Rangan (2005)** laid the foundation for fly ash-based geopolymer concrete development, emphasizing the influence of curing temperature, activator concentration, and mix design on strength and workability. They reported that elevated curing temperatures (60–80°C) were essential for the development of sufficient compressive strength in fly ash-based mixes, although such requirements pose limitations for field applications.

Later studies, including **Deb et al. (2014)**, focused on ambient curing strategies and showed that blending fly ash with slag improves setting time and early strength gain without the need for thermal curing. The authors demonstrated that the use of sodium silicate with appropriate fly ash/slag ratios enhances the polymerization process and densifies the microstructure.

However, the ambient curing performance of pure fly ash geopolymers remains a challenge. Research by **Pandey et al. (2024)** emphasized the critical role of **NaOH molarity and curing conditions**, showing that compressive strength and durability are highly sensitive to changes in these parameters.

2.2 GGBS-Based Geopolymer Concrete

GGBS, a calcium-rich material, when used either independently or in combination with fly ash, promotes the formation of **C–S–H and C–A–S–H gels**, which are structurally different from the N–A–S–H gels dominant in fly ash systems. The work of **Albitar et al. (2015)** and **Al-Majidi et al. (2015)** confirmed that GGBS inclusion enhances **early strength, reduces setting time, and enables ambient curing**, making it highly suitable for precast and field applications. These researchers also found that GGBS-based systems offer better **acid and sulfate resistance**, reduced porosity, and lower shrinkage rates.

Wang et al. (2020) provided a detailed analysis of the **microstructure and mechanical performance** of GGBS and FA-based geopolymer concretes. Their results highlighted that incorporating GGBS into fly ash mixes resulted in refined pore structures and increased compressive strength due to the synergistic formation of hybrid binding gels.

In a study of binder optimization, **Rajashekar and Ranganath (2023)** explored various activator concentrations in GGBS-rich geopolymer systems, confirming that mix design variables, particularly alkaline solution ratios, play a crucial role in strength development and setting behavior.

2.3 Fly Ash–GGBS Blended Geopolymer Systems

Blending fly ash and GGBS has proven to be an effective strategy to overcome the limitations of both materials. **Nath and Sarker (2014)** conducted systematic experiments to evaluate the effects of GGBS content on fly ash-based geopolymer mixes cured at ambient temperature. They found that GGBS additions significantly improved early strength, setting time, and workability. These findings are in line with the broader trend in geopolymer research, where **hybrid binders** are engineered for optimal performance.

Adak et al. (2014) demonstrated that the addition of **nano-silica** to FA-GGBS geopolymer mortar further enhances compressive strength and durability, especially under aggressive exposure conditions. This is attributed to better particle packing, denser gel formation, and pore refinement due to the nano-filler effect.

Similarly, **Asha and Antony (2020)** assessed fiber-reinforced FA-GGBS geopolymer concrete and reported substantial gains in tensile strength and crack resistance. Their study further reinforced the importance of microstructural enhancement in hybrid geopolymer systems.

From a thermal resistance perspective, **Hadi et al. (2019)** examined FA-GGBS geopolymer concrete under elevated temperatures and found that hybrid systems exhibit **superior thermal stability**, mechanical integrity, and residual strength compared to OPC or single-precursor geopolymers.

2.4 Durability and Microstructural Insights

Several researchers have focused on understanding the durability behavior of geopolymer concretes, particularly with regard to **acid attack**, **chloride penetration**, **sulfate resistance**, and **leachability**. The work by **Azarsa and Gupta (2020)** on potassium-based geopolymers showed that FA-GGBS systems resist acid and sulfate attack more effectively than OPC counterparts, primarily due to the absence of calcium hydroxide and denser gel structures.

Puertas et al. (2000) and **Criado et al. (2005)** conducted in-depth analyses of the **hydration and polymerization mechanisms**, revealing how variations in the SiO_2/Na_2O molar ratio and activator concentration affect gel type, crystalline phase formation, and long-term strength evolution. Their FTIR and XRD studies provided early evidence of the molecular mechanisms involved in alkali activation.

Chen et al. (2018) expanded this by examining the **co-activation of GGBS and sewage sludge ash**, noting that even secondary waste materials can contribute to strength and durability improvements when appropriately combined in geopolymer formulations.

2.5 Review Studies and Research Trends

Several review papers have contributed to synthesizing the experimental knowledge base. **Li et al. (2019)** comprehensively reviewed **mix design methodologies** for geopolymer concrete, offering practical insights into precursor selection, activator optimization, and target performance criteria. Their work emphasized the importance of balancing reactivity, setting time, workability, and strength through controlled binder chemistry.

Singh et al. (2015) and **Zhang et al. (2010, 2014)** provided broad perspectives on the **applications, advantages, and sustainability** of geopolymer concretes. They identified critical areas such as long-term durability, lifecycle carbon reduction, and potential industrial applications including precast elements, high-temperature-resistant structures, and waste management. **Duxson et al. (2007)** framed the **current state of geopolymer research**, addressing challenges such as activator cost, standardization, and field implementation.

Lastly, **Agrawal et al. (2017)** contributed to regional perspectives by analyzing the compressive strength behavior of fly ash concretes, showcasing practical experimentation using locally available materials.

2.6 Summary of Observations from Literature

- Fly ash-based GPC offers superior long-term strength and chemical resistance but generally requires heat curing.
- GGBS-based GPC enhances early strength, improves ambient curing feasibility, and densifies the matrix.
- Blending FA and GGBS produces hybrid systems with balanced mechanical and durability performance.
- Activator composition, curing method, and additives (e.g., nano-silica, fibers) significantly influence outcomes.
- Current literature shows wide variability in mix design practices, indicating the need for further standardization and optimization.

3. Conclusion

Geopolymer concrete represents a significant advancement in the pursuit of sustainable and high-performance construction materials. This review has critically examined and compared the behavior of **fly ash (FA)-based**,

GGBS-based, and **blended FA-GGBS geopolymer concretes** in terms of their mechanical performance, durability, microstructure, and practical applicability.

The literature reveals that **fly ash-based geopolymers** excel in long-term strength development, chemical resistance, and thermal stability, especially when cured under elevated temperatures. However, their reliance on heat curing limits their use in ambient or in-situ conditions. On the other hand, **GGBS-based geopolymers** offer rapid setting and superior early-age strength, making them more practical for structural applications that demand early formwork removal and faster construction cycles. Yet, their higher calcium content can lead to shrinkage and microcracking if not properly controlled.

Hybrid systems combining FA and GGBS emerge as the most promising approach, integrating the long-term durability of fly ash with the strength development characteristics of slag. These blended binders demonstrate improved workability, reduced curing demands, and enhanced resistance to environmental degradation. Studies have also shown that the synergy between N–A–S–H and C–A–S–H gel formation contributes to improved matrix densification and microstructural integrity.

Moreover, the performance of geopolymer concrete is highly sensitive to parameters such as **FA/GGBS ratio, activator concentration, curing regime, and additive use (e.g., nano-silica, fibers)**. These factors must be carefully optimized to meet specific performance criteria and environmental conditions.

Despite the progress made, challenges remain in terms of **standardized mix design procedures, long-term field validation, and scaling up production**. Future research should focus on developing practical guidelines for mix proportioning, advancing low-cost activators, exploring ambient curing mechanisms, and validating the long-term durability of geopolymer concrete in real-world conditions.

In conclusion, geopolymer concrete—particularly FA-GGBS blended systems—holds strong potential to replace OPC-based concrete in various structural and infrastructure applications, contributing meaningfully to **low-carbon construction** and **waste valorization**. Continued interdisciplinary research and collaboration between academia, industry, and policy makers are essential to realize the full potential of this green technology.

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