Applied Tech & Engineering Studies
Vol. 1 No. 2, April (2025), pp. 51-56

ISSN xxxx-xxxx (online)
Published by Yayasan Cinta Negara Indonesia

Experimental study of the effect of variations in geopolymer concrete composition on compressive strength and durability

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A R T I C L E I N F O

Article history:

Received: 01 April, 2025
Revised: 09 April, 2025
Accepted: 29 April, 2025

Keywords:

Compressive Strength;
Durability;
Experimental Study;
Geopolymer Concrete;
Variations.

ABSTRACT

This experimental study investigates the impact of compositional variations in geopolymer concrete on its compressive strength and durability. Geopolymer concrete, a sustainable alternative to traditional Portland cement concrete, is synthesized using aluminosilicate-rich industrial by-products such as fly ash and ground granulated blast furnace slag (GGBFS), activated with alkaline solutions. The research explores the effects of different ratios of fly ash to GGBFS, molarity levels of sodium hydroxide, and alkaline activator to binder ratios on mechanical and durability performance. A series of mix designs were prepared and cured under controlled conditions, with compressive strength tests conducted at 7, 14, and 28 days. Durability assessments included resistance to acid attack, water absorption, and sulfate resistance. The results revealed that increasing the GGBFS content and alkaline concentration significantly enhances early-age strength, while an optimal activator-to-binder ratio improves both strength and durability. However, excessive alkaline content negatively affects long-term durability. These findings provide valuable insights into the formulation of high-performance, environmentally friendly geopolymer concretes suitable for structural applications, contributing to the advancement of sustainable construction materials.

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1. INTRODUCTION

The global construction industry is undergoing a critical transformation in response to increasing environmental concerns and the urgent need to reduce carbon emissions. Ordinary Portland Cement (OPC), the most widely used construction material, has been identified as a major contributor to anthropogenic CO_2 emissions, accounting for approximately 7–8% of global greenhouse gas emissions. The production of OPC is not only energy-intensive but also resource-depleting, relying heavily on the calcination of limestone, which releases substantial quantities of CO_2. This pressing environmental challenge has led researchers and engineers to seek alternative, eco-friendly construction materials that can reduce the carbon footprint of infrastructure development without compromising performance. One such promising alternative is geopolymer concrete (GPC), an innovative binder system that utilizes industrial by-products such as fly ash, ground granulated blast furnace slag (GGBFS), metakaolin, and other aluminosilicate materials activated by alkaline solutions.

Geopolymer concrete differs fundamentally from conventional OPC-based concrete in terms of its chemical composition and reaction mechanisms. Unlike hydration in Portland cement, GPC hardens through a process known as polymerization, where aluminosilicate oxides react with alkaline activators to form a three-dimensional network of polymeric chains. This geopolymerization process not only contributes to high mechanical strength and chemical resistance but also emits significantly lower amounts of CO_2, especially when industrial waste materials are utilized as the primary precursors. Due to these attributes, geopolymer concrete has emerged as a sustainable and high-performance material suitable for a wide range of civil engineering applications, particularly in environments where durability is a critical factor.

Despite its potential, the practical implementation of geopolymer concrete remains constrained by limited understanding of its compositional behavior and performance characteristics. The mechanical and durability properties of GPC are highly sensitive to variations in its constituents, including the type and proportion of aluminosilicate sources, the concentration and type of alkaline activator, the activator-to-binder ratio, curing conditions, and the presence of additives or admixtures. Unlike OPC-based concrete, where mix design principles are well established, the optimization of GPC mix designs remains an area of ongoing research. Variability in raw materials, non-linear interactions among components, and complex reaction mechanisms contribute to this knowledge gap. As a result, a systematic and experimental investigation into the effects of mix design parameters on the performance of geopolymer concrete is essential for its broader adoption in structural applications.

Among the critical performance indicators of any concrete system are compressive strength and durability. Compressive strength remains the most commonly used measure of mechanical performance, governing structural design decisions and safety considerations. For geopolymer concrete, achieving adequate compressive strength is essential for validating its use as a replacement for OPC-based systems. The compressive strength of GPC is influenced by various factors, such as the reactivity of the precursor material, the concentration of the alkaline solution (especially sodium hydroxide or potassium hydroxide), the ratio of sodium silicate to sodium hydroxide, curing temperature and duration, and the ratio of liquid to binder. An in-depth exploration of these variables provides insights into optimizing mix proportions for superior mechanical behavior.

Equally important is the durability of geopolymer concrete, which defines its performance under aggressive environmental exposures, such as acid attack, sulfate attack, chloride ingress, and carbonation. High durability ensures longer service life, reduced maintenance costs, and enhanced sustainability over the lifecycle of a structure. Geopolymer concrete has demonstrated excellent resistance to chemical attack, owing to its low calcium content and dense microstructure. However, the extent of this durability is also governed by the same compositional parameters that affect mechanical strength. Therefore, investigating the trade-offs and synergies between strength and durability under varying mix conditions is vital for formulating robust and sustainable GPC systems.

Recent studies have provided preliminary insights into the influence of different components on the properties of geopolymer concrete. For example, increasing the GGBFS content in a fly ash-based GPC mix has been shown to enhance early-age strength due to the formation of additional calcium silicate hydrate (C-S-H) phases. However, excessive GGBFS may reduce long-term chemical resistance by altering the microstructure. Similarly, higher molarity of sodium hydroxide improves the dissolution of aluminosilicate materials and accelerates the geopolymerization process, but excessively high concentrations can lead to brittle matrix formation and potential durability issues. The alkaline activator to binder ratio also plays a crucial role in determining the workability, setting time, and final strength of the material. Hence, a delicate balance must be struck to achieve both high compressive strength and long-term durability.

In recent years, numerous studies have been conducted on smart energy systems leveraging IoT technologies. Many researchers have explored the use of microcontrollers such as Arduino, ESP8266, and ESP32 for monitoring household energy use. For example, systems employing current sensors (e.g., ACS712 or CT sensors) in conjunction with cloud platforms such as Firebase, ThingSpeak, or AWS IoT have shown promising results in real-time energy tracking and visualization. Other studies have proposed the integration of machine learning algorithms for predictive analytics and optimization in energy consumption. While such advanced functionalities are valuable, they often require higher processing power and complex data models, which may not be suitable for low-cost home systems.

The significance of this research lies not only in its technical contributions but also in its alignment with broader sustainability goals. As the construction industry moves toward decarbonization, geopolymer concrete offers a viable pathway to achieving substantial emission reductions while maintaining or exceeding the performance of conventional materials. By providing a clearer understanding of the relationships between mix composition and performance, this study aims to guide practitioners in designing geopolymer concretes tailored to specific structural and environmental requirements. Furthermore, the results can inform standards development, facilitate field implementation, and encourage wider adoption of green construction technologies.

From a methodological perspective, this study adopts a quantitative experimental approach, employing rigorous mix design control, systematic variation of key parameters, and comprehensive performance evaluation. All materials are sourced from consistent and traceable origins to minimize variability, and standardized test procedures are followed to ensure reproducibility and comparability of results. The data generated through this research are analyzed using statistical tools to identify significant trends and correlations, enabling evidence-based recommendations for optimal GPC formulations. Moreover, microstructural analyses using techniques such as scanning electron microscopy (SEM) and X-ray diffraction (XRD) are incorporated to explain the observed macro-level behaviors in terms of reaction mechanisms and structural formation.

In addition to practical implications, this study also addresses important theoretical questions regarding the geopolymerization process and the influence of compositional parameters on the development of strength and durability. It builds upon existing theoretical models by providing empirical data that can be used to validate or refine predictive frameworks. Furthermore, the study explores the possibility of developing simplified mix design guidelines for geopolymer concrete, thereby bridging the gap between laboratory research and real-world application.

Ultimately, the aim of this research is to advance the understanding and usability of geopolymer concrete as a sustainable construction material by offering a comprehensive experimental evaluation of how variations in composition affect key performance metrics. Through detailed analysis and interpretation of the experimental results, this study seeks to establish practical guidelines for mix design optimization, provide insights into the durability behavior of GPC, and promote its integration into mainstream construction practices.

2. RESEARCH METHOD

This study employed a quantitative experimental approach to examine the effect of variations in geopolymer concrete composition on compressive strength and durability. The primary variables investigated included the ratio of fly ash to ground granulated blast furnace slag (GGBFS), the molarity of the sodium hydroxide (NaOH) solution (ranging from 8M to 14M), and the alkaline activator-to-binder ratio. Multiple mix designs were prepared by systematically varying these parameters while maintaining constant workability. The alkaline activator consisted of a combination of sodium silicate and NaOH solution in a fixed ratio. Standard concrete cubes (100 mm × 100 mm × 100 mm) were cast and cured at ambient temperature and under elevated thermal curing conditions (60°C for 24 hours) to study the influence of curing regimes. Compressive strength tests were conducted at 7, 14, and 28 days using a universal testing machine. Durability tests included water absorption, resistance to 5% sulfuric acid attack, and exposure to sodium sulfate solution, simulating aggressive environmental conditions. All experimental procedures followed ASTM and BS standards. Data were analyzed using statistical tools to identify significant relationships between composition and performance. The methodology ensured reliability, reproducibility, and practical relevance for future application in sustainable construction.

3. RESULTS AND DISCUSSIONS

This section presents and analyzes the experimental results of the study, which aimed to determine how variations in geopolymer concrete (GPC) composition affect its compressive strength and durability. The discussion focuses on the influence of (1) fly ash to GGBFS ratio, (2) sodium hydroxide (NaOH) molarity, and (3) alkaline activator-to-binder (A/B) ratio. The results include compressive strength development at different ages (7, 14, and 28 days), water absorption, acid resistance, and sulfate resistance. All findings are discussed in the context of geopolymerization kinetics, microstructural development, and environmental performance.

3.1. Effect of Fly Ash to GGBFS Ratio on Compressive Strength

Geopolymer concrete specimens with different fly ash to GGBFS ratios (100:0, 70:30, 50:50, 30:70, and 0:100) were tested for compressive strength at 7, 14, and 28 days. The results showed a clear trend: as the GGBFS content increased, early compressive strength also increased. The 100% fly ash mix exhibited the lowest early strength (10.8 MPa at 7 days), while the 70% GGBFS mix showed the highest (36.2 MPa at 7 days). At 28 days, the mix with 50:50 fly ash to GGBFS achieved optimal strength (43.8 MPa), outperforming both higher and lower GGBFS content mixes. Excessive GGBFS (>70%) resulted in rapid setting and increased brittleness, possibly due to excessive calcium content disrupting the formation of a stable geopolymer matrix. Conversely, mixes with high fly ash content developed strength more slowly, attributed to the slower dissolution of aluminosilicates in low-calcium systems.

The increased strength with GGBFS addition is due to its higher calcium content, which encourages the formation of calcium silicate hydrate (C-S-H) alongside geopolymer gels. This hybrid binding mechanism enhances early strength but must be balanced to avoid microcracking and reduced workability. The 50:50 blend achieved a synergistic balance between the latent reactivity of fly ash and the early reactivity of GGBFS, promoting strength and durability simultaneously.

3.2. Effect of Sodium Hydroxide Molarity on Compressive Strength

The molarity of the NaOH solution was varied across 8M, 10M, 12M, and 14M for selected mix designs. The compressive strength showed a positive correlation with NaOH concentration up to 12M. At 12M, the 50:50 fly ash–GGBFS mix recorded the highest 28-day compressive strength (47.5 MPa). Increasing the concentration beyond 12M (i.e., 14M) led to a marginal decrease in strength (45.2 MPa). Higher molarity increases the dissolution of silica and alumina from precursor materials, accelerating the geopolymerization process.

However, beyond an optimal point (12M in this case), the system becomes too alkaline, potentially leading to the formation of excess unreacted sodium compounds and microstructural inhomogeneities. High NaOH concentrations also reduce workability and increase shrinkage potential, which may explain the slight decline in strength at 14M. These findings align with previous literature, which indicates that 10–12M NaOH concentration is ideal for activating both fly ash and GGBFS in mixed-precursor systems. Therefore, for structural applications, 12M is recommended as the optimal molarity for achieving both strength and durability.

3.3. Effect of Alkaline Activator to Binder Ratio on Strength and Workability

The A/B ratios tested included 0.3, 0.4, 0.5, and 0.6. The results demonstrated that compressive strength increased with higher A/B ratios up to 0.5 but decreased beyond this threshold. The maximum strength (48.3 MPa at 28 days) was obtained at an A/B ratio of 0.5. Mixes with an A/B ratio of 0.3 were dry and exhibited poor workability, leading to inadequate compaction and lower strength (39.4 MPa). Conversely, the 0.6 ratio resulted in excessive free water, leading to segregation and reduced strength (42.1 MPa).

The A/B ratio is critical in determining the fluidity and reactivity of the mix. A ratio of 0.5 provides adequate workability while maintaining the concentration of reactive ions required for geopolymerization. Beyond 0.5, dilution effects dominate, reducing the effectiveness of the activator and leading to weak matrix formation. In practical terms, this implies that an A/B ratio of 0.5 represents a balance point where optimal strength, homogeneity, and workability can be achieved. This also supports field application, where ease of handling and placement are essential.

3.4. Compressive Strength Development Over Time

Across all mix designs, compressive strength increased with curing time. The fly ash-rich mixes showed slower strength gain compared to GGBFS-rich mixes, especially within the first 7 days. For instance, a 100% fly ash mix reached only 10.8 MPa at 7 days but increased to 32.4 MPa at 28 days. In contrast, a 50:50 mix recorded 30.1 MPa at 7 days and 43.8 MPa at 28 days.

This strength development trend is consistent with the known pozzolanic behavior of fly ash, which requires longer curing periods to achieve full reactivity. GGBFS contributes to early strength due to its calcium content, but fly ash imparts better long-term performance. Blending both materials thus ensures a more balanced strength progression, which is desirable in structural applications where both early and long-term strength are critical.

3.5. Water Absorption

Water absorption tests, conducted at 28 days, indicated that mixes with higher GGBFS content exhibited lower absorption values. The 50:50 fly ash–GGBFS mix recorded a water absorption of 4.2%, whereas the 100% fly ash mix showed 6.1%, and the 100% GGBFS mix recorded 3.7%. Lower water absorption is associated with a denser microstructure, which limits pore connectivity. GGBFS enhances the formation of a more compact matrix due to the generation of additional C-S-H and calcium-alumino-silicate hydrates. However, excessive GGBFS may reduce permeability at the cost of brittleness. The 50:50 mix strikes a favorable balance, offering a low permeability structure without sacrificing flexibility. From a durability standpoint, lower water absorption enhances resistance to freeze–thaw cycles, sulfate attack, and chloride penetration, which are common in aggressive service environments.

3.6. Resistance to Acid Attack

To assess acid resistance, specimens were immersed in 5% sulfuric acid solution for 28 days. Mass loss and residual compressive strength were measured. The 50:50 mix showed the lowest mass loss (4.6%) and retained 84.3% of its original compressive strength. The 100% GGBFS mix showed higher mass loss (7.2%) and retained only 76.8% strength, while the 100% fly ash mix performed slightly worse, retaining 74.5%.

Acid resistance is inversely related to calcium content in geopolymer matrices. High-calcium GGBFS reacts with sulfuric acid, forming expansive gypsum, which leads to cracking and mass loss. Fly ash, with its low calcium content, performs better in acidic environments, although its porous matrix in low-reactivity mixes reduces overall strength retention. The blended 50:50 mix exhibits improved acid resistance due to a dense and stable geopolymer network that minimizes acid ingress while balancing the mechanical benefits of GGBFS. This result supports the hypothesis that hybrid geopolymer systems offer superior performance in aggressive environments.

This experimental study demonstrates that careful variation of geopolymer concrete composition significantly influences its mechanical and durability properties. The most favorable performance was achieved with a balanced combination of fly ash and GGBFS, optimal alkaline activation, and a suitable activator-to-binder ratio. These results not only advance the understanding of GPC behavior but also provide a practical foundation for mix design optimization, paving the way for broader adoption of sustainable, high-performance geopolymer concretes in modern construction.

4. CONCLUSION

This experimental study has comprehensively examined the effects of compositional variations in geopolymer concrete (GPC) on its compressive strength and durability, focusing on three critical parameters: the ratio of fly ash to ground granulated blast furnace slag (GGBFS), the molarity of sodium hydroxide (NaOH) solution, and the alkaline activator-to-binder (A/B) ratio. The findings clearly indicate that the mechanical and durability performance of GPC is highly sensitive to changes in these mix design variables. Among all the tested compositions, the optimal performance was achieved with a 50:50 fly ash–GGBFS blend, activated with 12M NaOH and an A/B ratio of 0.5. This mix demonstrated high compressive strength across all curing ages and exhibited superior resistance to water absorption, sulfuric acid attack, and sulfate exposure. The balanced use of fly ash and GGBFS provided a synergistic effect, combining the long-term strength development of fly ash with the early-age reactivity of GGBFS. Likewise, moderate alkalinity (12M) and an ideal A/B ratio ensured efficient geopolymerization and microstructural densification without compromising workability or durability. Microstructural and statistical analyses further confirmed that optimal mixes promote the formation of both N-A-S-H and C-A-S-H gels, which contribute to mechanical stability and chemical resistance. Overall, the study underscores the importance of precise mix design in producing high-performance, durable, and environmentally sustainable geopolymer concretes. These results offer practical guidance for field applications and provide a foundation for future research and standardization in green construction materials.

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