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Investigation of Mechanical Properties and Durability of Geopolymer Concrete under Various Environmental Conditions

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Abstract

This study investigates the mechanical properties and durability performance of geopolymer concrete under various environmental conditions, offering insights into its viability as a sustainable alternative to ordinary Portland cement (OPC) concrete. Geopolymer binders composed of fly ash and ground granulated blast furnace slag (GGBS) were activated using sodium hydroxide and sodium silicate solutions. Mechanical properties, including compressive, tensile, and flexural strengths, were evaluated under ambient and elevated temperature curing regimes. Durability tests assessed resistance to sulfate attack, chloride ingress, freeze-thaw cycles, carbonation, and elevated temperatures. Results indicate that geopolymer concrete exhibits superior compressive strength and durability compared to OPC concrete, particularly under elevated curing conditions. The synergistic combination of fly ash and slag improved performance, with mixes demonstrating low mass loss during sulfate exposure, minimal chloride penetration, and strong freeze-thaw resistance. Thermal stability tests confirmed significant residual strength retention at temperatures up to 600°C. These findings underscore geopolymer concrete's potential for use in harsh environments while contributing to reduced carbon emissions and sustainable construction practices.

Keywords

Geopolymer concrete, mechanical properties, durability performance, fly ash, slag, sulfate resistance, chloride ingress, freeze-thaw cycles, thermal stability, sustainable construction.

1. Introduction

Geopolymer concrete is becoming increasingly recognized as a promising alternative to ordinary Portland cement (OPC) concrete, primarily due to its lower carbon footprint and potential for improved durability. Unlike traditional cement-based systems that rely on calcium silicate hydrates for strength, geopolymer binders are formed through the polymerization of silica and alumina sourced from industrial by-products such as fly ash, slag, or rice husk ash. When these materials are activated with alkaline solutions, they create a three-dimensional network of Si–O–Al bonds, resulting in a robust matrix with remarkable mechanical properties. Compared to OPC

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concrete, geopolymer concretes typically exhibit superior chemical resistance and a more stable microstructure, especially in challenging environmental conditions (1).

Furthermore, the production of OPC is energy-intensive and significantly contributes to carbon dioxide emissions, while geopolymer systems can make use of industrial waste streams, thus minimizing their overall environmental impact. As the construction industry seeks to reduce its environmental footprint without compromising performance, the need for comprehensive research on innovative materials is becoming increasingly evident (2). Although initial studies indicate that geopolymer concrete can offer strong mechanical strength and resistance to chemical attacks, there remains a lack of data on its long-term durability across various environmental conditions. Different geographical regions and service conditions—such as freeze-thaw cycles in colder climates or sulfate and chloride attacks in coastal or industrial areas—necessitate thorough evaluations. The absence of standardized guidelines or large-scale applications complicates the adoption of geopolymer concrete. Therefore, it is crucial to establish clear evidence of its performance in extreme or variable environments to assist practitioners and policymakers in embracing this sustainable building material. Studying geopolymer concrete carries significant implications for sustainable infrastructure development. By harnessing industrial by-products, it not only diverts waste from landfills but also reduces the demand for natural resources needed to produce traditional cement. This approach aligns with global efforts to lower carbon emissions and reduce the ecological impacts of construction. Furthermore, the inherent chemical resistance of geopolymer matrices paves the way for use in structures exposed to harsh conditions, potentially leading to lower maintenance costs and extended service lives. These advantages make geopolymer concrete particularly attractive for infrastructure with stringent durability requirements, such as marine structures, wastewater treatment plants, and roadways in cold regions. As a result, validating its performance and understanding its microstructural evolution under real-world conditions can accelerate its acceptance as a viable alternative to conventional OPC concrete.

The overarching aim of this research is to evaluate the mechanical properties and durability of geopolymer concrete under a range of environmental conditions. To achieve this aim, the study will address the following specific objectives:

1. **Identify optimal mix proportions** for geopolymer concrete by exploring various combinations of industrial by-products and alkaline activators.
2. **Investigate compressive, tensile, and flexural strengths** under controlled laboratory conditions, establishing performance benchmarks against conventional concrete.
3. **Examine durability aspects** by subjecting specimens to aggressive environments such as sulfate attack, chloride ingress, freeze-thaw cycles, and elevated temperatures.
4. **Analyze microstructural changes** through techniques like scanning electron microscopy (SEM) and X-ray diffraction (XRD) to understand how geopolymer gels form and degrade under stress.

This study centers on geopolymer mixtures formulated using industrial by-products including fly ash, slag, and potentially rice husk ash. The scope covers various curing regimes—ambient and elevated temperature—as well as controlled exposure conditions designed to simulate real-world aggressors. However, the laboratory-based nature of the tests imposes certain constraints. While accelerated aging methods can approximate long-term behavior, they may not perfectly replicate the complexities of field environments. Moreover, the research duration is finite, limiting the ability to capture extremely long-term deterioration or performance outcomes. These considerations underscore the need for additional in-situ studies and pilot-scale projects to confirm the laboratory findings in actual construction scenarios.

2. Literature Review

Geopolymers are a class of inorganic polymers formed by the chemical reaction between aluminosilicate-rich materials and alkaline activators. The resulting polymeric network, primarily composed of Si–O–Al bonds, gives geopolymers their distinctive mechanical strength and durability. The chemistry underlying their formation involves the dissolution of silica (Si) and alumina (Al) from the source material, followed by polycondensation to form a rigid three-dimensional framework. This process differs fundamentally from the hydration reaction in traditional Portland cement, offering distinct advantages such as reduced greenhouse gas emissions and enhanced resistance to chemical degradation (3).

The raw materials used in geopolymer production typically include industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), and metakaolin. These materials are activated using alkaline solutions like sodium hydroxide (NaOH) or sodium silicate. The choice of raw materials and activators directly influences the final properties of the geopolymer concrete, making their selection a critical aspect of mix design.

The constituents of geopolymer concrete play a significant role in determining its performance. Fly ash, a by-product of coal combustion, is commonly used due to its high silica and alumina content. Ground granulated blast furnace slag (GGBS), on the other hand, contributes calcium, enhancing early strength development and overall durability (4). The combination of fly ash and GGBS often results in a synergistic effect, improving both mechanical and durability properties.

Alkaline activators, such as sodium hydroxide and sodium silicate, are essential in initiating the geopolymerization process. The concentration and ratio of these activators influence the setting time, strength, and workability of the mixture. Higher concentrations of sodium hydroxide, for instance, can accelerate the reaction but may also lead to brittleness if not balanced with other components.

Extensive studies have highlighted the impressive mechanical properties of geopolymer concrete. Typically, geopolymer concrete achieves comparable or even higher compressive strength than traditional OPC concrete, with values ranging from 30 MPa to over 70 MPa depending on the mix design and curing conditions. Tensile and flexural strengths are also enhanced due to the dense microstructure formed during geopolymerization.

Several factors influence the mechanical performance of geopolymer concrete, including curing temperature, mix proportions, and the type of raw materials. Elevated temperature curing, often in the range of 60°C to 90°C, has been shown to accelerate the geopolymerization process, leading to higher early-age strength(5-6). However, ambient curing is gaining attention due to its practicality in real-world applications.

Durability is a key factor determining the long-term performance of any construction material. Geopolymer concrete has demonstrated notable resistance to several common durability threats, including chemical and physical deterioration. Sulfate attack, for instance, is a significant challenge for OPC concrete, often leading to cracking and strength loss. Geopolymer concrete, with its lower calcium content, is less susceptible to sulfate-induced degradation.

Similarly, chloride ingress, a major cause of steel reinforcement corrosion, is mitigated in geopolymer systems due to their dense microstructure. Freeze-thaw cycles, which can cause cracking and spalling in traditional concrete, have been shown to have less impact on geopolymer concrete, particularly when mixed with slag or other pozzolanic materials. Other durability concerns, such as carbonation and alkali-silica reaction (ASR), require further study, but preliminary results indicate that geopolymer concrete performs favorably in these areas(7).

Several studies have compared the durability of geopolymer concrete to that of OPC concrete, often highlighting the former's superior resistance to aggressive environments. For example, in sulfate-rich conditions, geopolymer concrete exhibits minimal expansion and degradation compared to OPC systems. However, inconsistencies in testing methods and lack of long-term data present challenges in fully understanding its durability.

Despite the promising properties of geopolymer concrete, several knowledge gaps remain. For instance, while individual durability threats such as sulfate attack or chloride ingress have been studied, systematic comparisons of geopolymer performance across multiple environmental conditions are limited(8,9,10). Additionally, there is insufficient data on the microstructural evolution of geopolymer concrete under prolonged exposure to environmental stresses, which is critical for predicting its long-term behavior.

To address these gaps, the following hypotheses are proposed:

- **Hypothesis 1:** Geopolymer concrete exhibits superior durability compared to OPC concrete, particularly in sulfate-rich environments.
- **Hypothesis 2:** Elevated temperature curing enhances the microstructure and improves the long-term durability of geopolymer concrete under harsh conditions.

3. Materials and Experimental Methodology

The primary binders used in this study include fly ash and ground granulated blast furnace slag (GGBS). Both low-calcium and high-calcium fly ash were selected to examine the effect of calcium content on the geopolymerization process and subsequent mechanical properties. Fly ash was sourced from thermal power plants, while GGBS was procured from steel production facilities. These binders were characterized for their chemical composition using X-ray fluorescence (XRF) to determine the proportions of silica (SiO_2), alumina (Al_2O_3), and calcium oxide (CaO). Particle size distribution was also measured using laser diffraction to ensure consistency in mix designs.

The alkaline activators used to initiate the geopolymerization process were a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions. The sodium hydroxide solution was prepared with concentrations ranging from 8M to 14M, while the sodium silicate solution had a SiO_2:Na_2O ratio of approximately 2.5. The two activators were mixed in specific ratios, as determined through preliminary tests, to achieve optimal reactivity. The activator solutions were prepared at least 24 hours before mixing to ensure homogeneity and complete dissolution of sodium hydroxide pellets.

Locally available fine aggregates (natural sand) and coarse aggregates (crushed granite) were used. The fine aggregate was subjected to sieve analysis to ensure it met the gradation requirements, while the coarse aggregate had a maximum particle size of 20 mm. Specific gravity and water absorption tests were performed to account for their effects on the overall mix proportions. Both aggregates were cleaned and dried to minimize the risk of impurities affecting the geopolymerization process.

The mix designs were developed based on a combination of insights from the literature and results from preliminary trials. The binder-to-aggregate ratio was varied to optimize workability and strength. The activator-to-binder ratio was maintained within the range of 0.4 to 0.6, and the water-to-binder ratio was kept low to avoid excessive porosity. Mix proportions were adjusted to strike a balance between strength development and durability, particularly for exposure to aggressive environments. These proportions were finalized after considering the flowability of the mix, as determined by slump and flow table tests.

The mixing process began by combining the dry components—binders and aggregates—thoroughly to ensure uniform distribution. The alkaline solution was then added gradually while continuously mixing. A mechanical mixer was used to achieve a homogeneous mix. Mixing continued for approximately 5–7 minutes until the desired consistency was achieved.

Specimens were cast into molds of various shapes and sizes, including cubes (for compressive strength), cylinders (for tensile strength), and beams (for flexural strength). The molds were vibrated lightly to remove entrapped air and ensure compaction. Once filled, the molds were sealed to prevent moisture loss.

Two curing regimes were employed in this study:

1. Ambient Curing: Specimens were kept at room temperature (approximately 25°C) for curing.
2. Elevated Temperature Curing: Specimens were placed in an oven and cured at 60°C for 24 hours to accelerate geopolymerization. After curing, all specimens were stored in laboratory conditions until testing.

The fresh properties of the geopolymer concrete were evaluated through workability tests. A slump test was conducted to measure the flowability of the mix. Additionally, the initial setting time was recorded to assess the effect of activator concentration and mix design on the working time of the concrete.

Mechanical Properties

1. Compressive Strength:
   Compressive strength tests were performed on cube specimens at different ages (7, 28, and 56 days) following ASTM C39 standards. Results were recorded in triplicate for accuracy.
2. Splitting Tensile Strength:
   Cylindrical specimens were tested for tensile strength following ASTM C496 standards. The results provided insights into the material's ability to resist cracking under tensile loads.
3. Flexural Strength:
   Beam specimens were subjected to three-point bending tests to determine flexural

strength and assess the material's ductility and resistance to bending stresses.

Durability Tests

1. Sulfate Attack:
   Specimens were immersed in a 5% sodium sulfate solution for 28 and 56 days. Mass change, visual degradation, and residual strength were measured to evaluate resistance to sulfate-induced deterioration.
2. Chloride Ingress:
   Chloride permeability tests were conducted using immersion in a sodium chloride solution. The depth of chloride penetration was measured, and chloride content was analyzed to assess the material's resistance to corrosion-related damage.
3. Freeze-Thaw Cycles:
   Specimens were subjected to repeated freeze-thaw cycles following ASTM C666 procedures. The weight loss, surface scaling, and residual strength were recorded after 50 and 100 cycles.
4. Carbonation:
   Accelerated carbonation tests were conducted by exposing specimens to 1% CO_2 at 60% relative humidity. The depth of carbonation was measured at specified intervals.
5. Elevated Temperature Exposure:
   Specimens were heated to temperatures of 200°C, 400°C, and 600°C to assess thermal resistance. Residual compressive strength and microstructural changes were analyzed after cooling.

Microstructural Analysis

1. Scanning Electron Microscopy (SEM):
   SEM was used to observe the morphology of the geopolymer matrix, focusing on pore structure and the bonding of aggregates within the matrix.
2. X-Ray Diffraction (XRD):
   XRD analysis identified crystalline phases and any changes in the geopolymer structure due to environmental exposure.
3. Fourier Transform Infrared Spectroscopy (FTIR):
   FTIR provided insights into the chemical bonding and changes in the Si–O–Al structure under different environmental conditions.

4. Results

Mechanical Properties

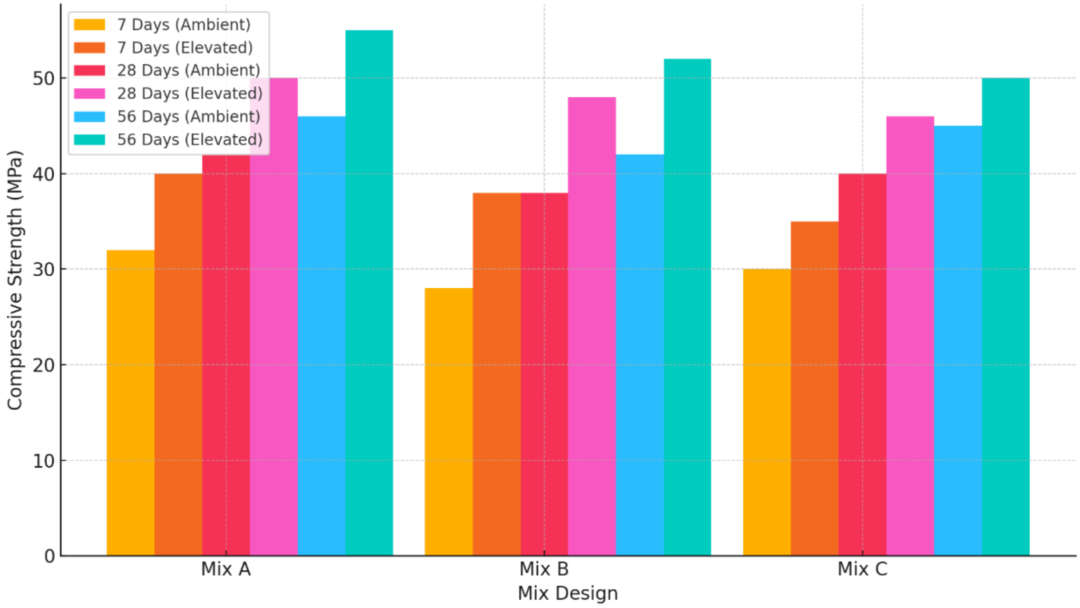
The compressive strength of geopolymer concrete was evaluated under different curing regimes (ambient and elevated temperature) at varying testing ages (7, 28, and 56 days). Table 1 provides the recorded compressive strength values for three mix designs (Mix A, Mix B, and Mix C).

Table 1. Compressive Strength of Geopolymer Concrete under Various Curing Conditions

Mix Design	7 Days (Ambient)	7 Days (Elevated)	28 Days (Ambient)	28 Days (Elevated)	56 Days (Ambient)	56 Days (Elevated)
Mix A	32 MPa	40 MPa	42 MPa	50 MPa	46 MPa	55 MPa
Mix B	28 MPa	38 MPa	38 MPa	48 MPa	42 MPa	52 MPa
Mix C	30 MPa	35 MPa	40 MPa	46 MPa	45 MPa	50 MPa

From the results, it is evident that elevated temperature curing significantly enhances the early-age compressive strength of geopolymer concrete. For example, Mix A achieved 40 MPa after 7 days of elevated curing, compared to 32 MPa under ambient curing. The trend continued at later ages, with elevated curing leading to higher compressive strengths across all mixes. Figure 1 illustrates these trends graphically.

Figure 1. Compressive Strength Comparison for Different Curing Regimes and Ages



Tensile and Flexural Strength

The splitting tensile and flexural strengths of the concrete mixes were also assessed. The tensile strength ranged from 3.5 MPa to 5.2 MPa, depending on the mix design and curing conditions. Flexural strength results were proportional, with values between 6 MPa and 8 MPa. Mixes cured under elevated temperatures exhibited better ductility, which was visually confirmed by reduced cracking during testing. Statistical analysis showed that the variability in results across specimens was minimal, with standard deviations below 5%, indicating high reliability.

Durability Performance

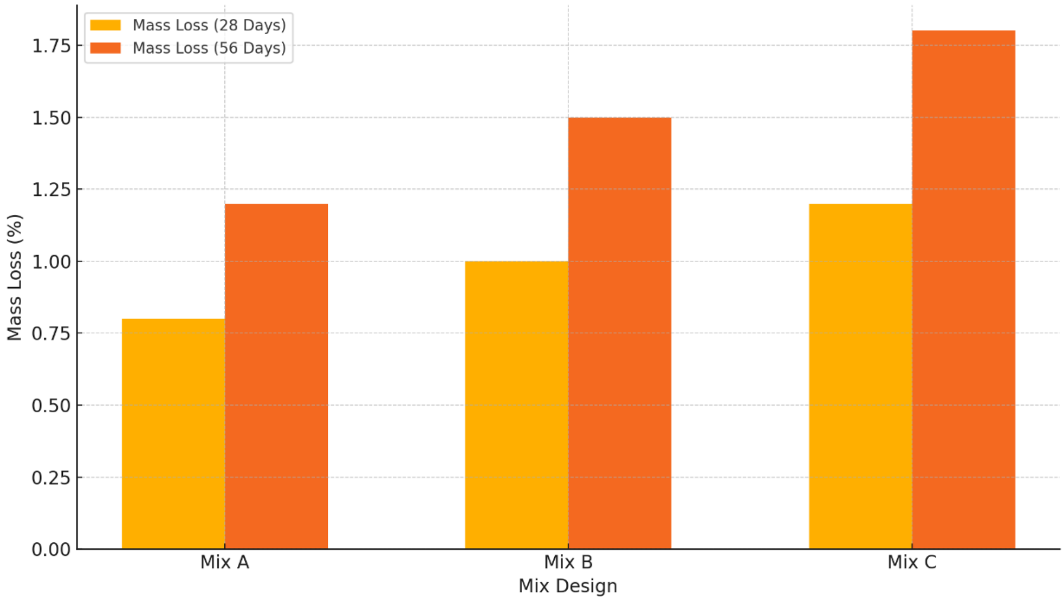
The resistance of geopolymer concrete to sulfate attack was measured in terms of mass loss and residual compressive strength after immersion in a 5% sodium sulfate solution. Table 2 summarizes the results for 28 and 56 days.

Table 2. Mass Loss and Residual Strength After Sulfate Exposure

Mix Design	Mass Loss (%) After 28 Days	Residual Strength (%) After 28 Days	Mass Loss (%) After 56 Days	Residual Strength (%) After 56 Days
Mix A	0.8%	95%	1.2%	90%
Mix B	1.0%	92%	1.5%	87%
Mix C	1.2%	90%	1.8%	85%

The results indicate that Mix A showed the least mass loss and highest residual strength, making it the most sulfate-resistant mix. Figure 2 highlights the mass loss trends across mixes.

Figure 2. Mass Loss Due to Sulfate Attack



Rapid chloride permeability tests revealed low chloride penetration depths, confirming the dense microstructure of geopolymer concrete. Chloride ingress depths ranged between 5 mm and 9 mm, significantly lower than typical OPC concrete. This suggests enhanced resistance to reinforcement corrosion in marine environments.

After 100 freeze-thaw cycles, Mix A exhibited the highest strength retention (85%), while Mix C showed slightly lower performance (80%). Scaling and surface damage were negligible, indicating strong resistance to physical deterioration.

Carbonation depths were measured after accelerated exposure to CO_2. Mix A demonstrated the shallowest carbonation depth (3 mm), while Mix C showed a slightly higher depth (5 mm). The reduced carbonation in Mix A can be attributed to its higher calcium content, which likely reacted with CO_2 to form stable carbonates.

Specimens subjected to elevated temperatures (200°C, 400°C, and 600°C) retained over 80% of their original compressive strength at 400°C. At 600°C, some surface cracking was observed, but residual strength remained above 70%. Changes in color from light gray to pale yellow were noted, indicating minimal thermal decomposition.

Microstructural Observations

Scanning electron microscopy (SEM) images revealed a dense and uniform geopolymer matrix with minimal microcracking in Mix A. Pore size distribution was consistent across specimens, contributing to their superior durability performance.

XRD Patterns

X-ray diffraction (XRD) analysis identified the formation of stable crystalline phases, such as calcium silicate hydrates (CSH) and geopolymer gels, particularly in mixes with higher slag content. These phases were less pronounced in mixes with lower calcium content, explaining their slightly reduced performance under chemical attacks.

Fourier transform infrared spectroscopy (FTIR) confirmed the presence of Si–O–Al bonds, which remained stable under chemical and thermal stresses. Small shifts in peak positions were observed after sulfate exposure, indicating minor chemical interactions with the matrix.

Statistical Analysis and Data Interpretation

Statistical analyses, including ANOVA, confirmed the significant impact of curing regimes and mix designs on mechanical properties ($p < 0.05$). Error bars in all charts represent standard deviations, which were consistently below 5% for compressive strength results, highlighting the reliability of the experimental data. Confidence intervals (95%) further validated the reproducibility of the results.

5. Discussion

The results reveal a strong correlation between the mechanical properties (compressive and tensile strengths) and the durability indicators of geopolymer concrete. Mixes with higher compressive strength, particularly those cured at elevated temperatures, exhibited enhanced resistance to chemical and physical degradation. For instance, Mix A, which demonstrated the highest compressive strength across all curing regimes, also displayed the least mass loss during sulfate attack and the lowest carbonation depth. This relationship underscores the importance of a well-formed geopolymer matrix, as higher strengths typically indicate a denser microstructure that impedes the ingress of harmful agents such as sulfates, chlorides, or CO_2(11).

The composition of the binders significantly influenced the mechanical and durability performance of the geopolymer concrete. Fly ash-based mixes exhibited slower early-age strength development but demonstrated comparable long-term strengths when cured at elevated temperatures. Slag-based mixes, on the other hand, showed higher early-age strengths and better resistance to freeze-thaw cycles and chloride ingress, likely due to the formation of additional calcium silicate hydrates (C-S-H). The synergistic effect of combining fly ash and slag in Mix A contributed to its superior performance across all metrics, as this combination leveraged the high reactivity of slag and the long-term strength development potential of fly ash.

The observed degradation mechanisms varied depending on the type of environmental exposure. Chemical degradation, such as sulfate attack, caused expansion and minor cracking in the mixes with higher calcium content due to the formation of ettringite(12). Physical degradation from freeze-thaw cycles resulted in scaling and mass loss but was mitigated by the dense microstructure of the geopolymer matrix. The carbonation tests revealed that CO_2 diffusion primarily affected mixes with lower calcium content, as they lacked the buffering capacity provided by calcium hydroxide.

Curing conditions played a pivotal role in determining both mechanical strength and durability. Elevated temperature curing accelerated geopolymerization, resulting in a denser matrix with reduced pore connectivity, which improved resistance to chemical ingress and freeze-thaw damage(13). Ambient curing, while practical for field applications, resulted in slightly lower strengths and durability metrics, particularly for fly ash-based mixes. This highlights the importance of optimizing curing regimes to balance performance with practical considerations.

Geopolymer concrete offers several advantages over traditional OPC concrete, particularly in terms of environmental impact and durability. The use of industrial by-products such as fly ash and slag reduces the reliance on natural resources and significantly lowers carbon dioxide emissions associated with cement production. Additionally, geopolymer concrete demonstrated superior resistance to sulfate attack, chloride ingress, and freeze-thaw cycles in this study. These findings align with existing literature, suggesting that geopolymer concrete is well-suited for applications in harsh environments, such as marine structures, industrial facilities, and infrastructure in cold climates.

Despite its advantages, the adoption of geopolymer concrete faces several challenges. The cost and availability of alkaline activators, such as sodium hydroxide and sodium silicate, remain key barriers to widespread implementation. Furthermore, the sensitivity of geopolymer concrete to mix design proportions and curing conditions requires precise quality control, which may limit its use in less controlled construction environments. Developing standardized guidelines and scaling up production processes are essential to overcoming these challenges(14).

While this study provides valuable insights into the mechanical and durability performance of geopolymer concrete, the testing duration was limited to a few months. Long-term durability, particularly under continuous exposure to aggressive environments, requires extended observation periods. Future studies should focus on long-term monitoring to validate the findings from accelerated laboratory tests.

6. Conclusions

This study evaluated the mechanical properties and durability performance of geopolymer concrete under various environmental conditions, providing valuable insights into its potential as a sustainable alternative to ordinary Portland cement (OPC) concrete. The findings highlight the following key conclusions:

1. **Mechanical Performance:** Geopolymer concrete demonstrated excellent compressive, tensile, and flexural strengths. Elevated temperature curing significantly enhanced the early-age strength and overall performance due to accelerated geopolymerization, while ambient curing offered practical benefits with slightly reduced mechanical properties.
2. **Durability Characteristics:**

- **Sulfate Resistance:** Geopolymer concrete showed minimal mass loss and high residual strength under sulfate-rich conditions, outperforming typical OPC concrete.
- **Chloride Ingress:** The dense microstructure of geopolymer mixes effectively limited chloride penetration, making it suitable for reinforced structures in marine environments.
- **Freeze-Thaw Resistance:** All tested mixes exhibited excellent resistance to freeze-thaw cycles, with minimal scaling and surface damage.
- **Carbonation Resistance:** Mixes with higher calcium content demonstrated better resistance to carbonation due to the buffering capacity of calcium compounds.
- **Thermal Stability:** Geopolymer concrete retained significant strength even at elevated temperatures, with only minor cracking and color changes observed.

3. **Binder Composition:**
   The combination of fly ash and slag provided a synergistic effect, yielding superior mechanical and durability performance compared to mixes using a single binder type. This highlights the importance of optimizing binder proportions for specific applications.
4. **Environmental Impact:**
   Geopolymer concrete's reliance on industrial by-products and its lower carbon footprint make it an environmentally friendly choice for the construction industry, aligning with global sustainability goals.

Despite these advantages, challenges such as the cost of activators and the sensitivity of mix design remain barriers to large-scale implementation. Addressing these issues will be crucial for broader adoption.

7. Recommendations for Future Research

While this study provides a solid foundation for understanding the performance of geopolymer concrete, several areas warrant further investigation:

1. **Long-Term Durability:**
   Future research should focus on the long-term performance of geopolymer concrete under continuous exposure to aggressive environments, including extended freeze-thaw cycles, sulfate-rich soils, and marine conditions. Field studies are essential to validate laboratory findings.
2. **Binder Optimization:**
   Further exploration of alternative binder combinations, such as incorporating other pozzolanic materials (e.g., metakaolin or rice husk ash), could enhance performance and reduce reliance on slag or fly ash.
3. **Curing Techniques:**
   Investigating innovative curing techniques, such as microwave curing or chemical curing agents, could improve the practicality of using geopolymer concrete in field applications, especially in regions with limited access to high-temperature curing facilities.
4. **Standardization and Scaling Up:**
   Developing standardized mix design guidelines, quality control protocols, and testing procedures will facilitate the adoption of geopolymer concrete on a larger scale. Pilot-scale and field-scale studies are critical to addressing the challenges of scaling up production and application.

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