Review on Strength, Durability, and Workability Characteristics of Geopolymer Concrete

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Abstract: Geopolymer concrete (GPC) has emerged as a promising sustainable alternative to conventional Portland cement concrete (PCC), offering a potential reduction in the construction industry's substantial greenhouse gas emissions. PCC production is a major contributor to CO2, and GPC, utilizing industrial by-products like fly ash and ground granulated blast furnace slag (GGBFS), presents a compelling solution. This review examines GPC, focusing on its strength, durability, and workability. GPC uses geopolymers as the binding agent—inorganic aluminosilicate materials synthesized through alkali activation of source materials. This geopolymerization process involves dissolving aluminosilicate precursors in a highly alkaline solution, forming a three-dimensional polymeric network. The use of industrial by-products like fly ash and GGBFS aligns with sustainable practices. GPC has demonstrated the potential for comparable or superior mechanical properties, particularly compressive strength, compared to PCC, especially with optimized mix designs and curing conditions. Research on the microstructure development of alkali-activated fly ash provides insights into strength development. GPC also offers potential durability improvements, notably in aggressive chemical environments like sulfate attack. However, challenges remain, including workability concerns. Optimizing mix design parameters, such as the SiO2/Na2O ratio of the alkali activator, is crucial for achieving desired workability without sacrificing other properties. Long-term durability in diverse environments requires further investigation, extending beyond sulfate resistance to include freeze-thaw cycles and chloride exposure. This review synthesizes research on GPC's strength (compressive, tensile, flexural), exploring the influence of source materials, alkali activators, curing conditions, and mix design. It also addresses durability aspects (chemical resistance, freeze-thaw, elevated temperature) and workability challenges. By synthesizing existing knowledge, this review aims to provide a comprehensive overview of GPC, contributing to the advancement and wider application of this sustainable construction material.

Index Terms–: Geopolymer Concrete (GPC), Strength, Durability, Workability, Fly Ash, Ground Granulated Blast Furnace Slag (GGBFS), Compressive Strength, Sustainability, Mix Design

I. INTRODUCTION

The construction industry is a significant contributor to global greenhouse gas emissions, primarily due to the production of Portland cement, the essential binder in conventional concrete [1]. This environmental burden has spurred extensive research into alternative, sustainable construction materials. Among these, geopolymer concrete (GPC) has emerged as a promising candidate, offering the potential to significantly reduce the industry's carbon footprint while maintaining or even enhancing material performance. GPC utilizes geopolymers as the binding agent, which are inorganic alumina silicate materials synthesized through the alkali activation of source materials like fly ash, ground granulated blast furnace slag (GGBFS), metakaolin, or other industrial by-products [2]. This process, known as geopolymerization, involves the dissolution of these aluminosilicate precursors in a highly alkaline solution, followed by polycondensation reactions that create a three-dimensional polymeric network [1]. Davidovits [1] pioneered the concept of geopolymers, laying the foundation for their application in various fields, including construction.

The shift towards GPC is driven by several key factors. Firstly, it offers a sustainable solution by utilizing industrial by-products, thereby reducing waste and minimizing the reliance on virgin resources. Fly ash, a pozzolanic material generated from coal combustion, is a widely used source material in GPC [2, 5]. Both low-calcium [2] and high-calcium fly ashes have been investigated, with Hardjito and Rangan [2] specifically exploring the development and properties of low-calcium fly ash-based GPC. GGBFS, a by-product of the iron and steel industry, is another valuable resource that can contribute to the geopolymerization process and enhance the properties of the resulting concrete [8]. Secondly, GPC has demonstrated the potential for superior mechanical properties compared to conventional concrete. Studies have shown that GPC can achieve comparable or even higher compressive strengths, especially with optimized mix designs and curing conditions [6, 10]. The microstructure development of alkali-activated fly ash, crucial for understanding strength development, has been extensively studied [3]. Thirdly, GPC offers potential improvements in durability, particularly in aggressive chemical environments. Research has explored its resistance to sulfate attack [4], highlighting its potential for applications where exposure to sulfates is a concern. Palomo et al. [5] emphasized the potential of alkali-activated fly ashes as a "cement for the future," highlighting their long-term performance and durability.

However, the widespread adoption of GPC faces several challenges. Workability, a crucial aspect of fresh concrete, can be a concern with GPC mixes [8]. [1] Optimizing the mix design, including the SiO2/Na2O ratio of the alkali activator [7], is essential for achieving desired workability without compromising other properties. Furthermore, the long-term durability of GPC in various environmental conditions requires further investigation. While studies have examined specific aspects like sulfate resistance [4], a comprehensive understanding of its performance in freeze-thaw cycles, chloride environments, and other aggressive conditions is necessary. This review paper focuses on the developments in geopolymer concrete research up to 2015, specifically examining its strength, durability, and workability characteristics. It explores the influence of various factors, including source materials, alkali activators, curing conditions, and mix design, on these key properties. The paper also compares geopolymer concrete with conventional concrete, highlighting its advantages and limitations, and discusses potential applications. By synthesizing the existing knowledge, this review aims to provide a comprehensive overview of the state-of-the-art of GPC research up to 2015, contributing to the advancement and wider application of this sustainable construction material [9].

II. Strength Characteristics of Geopolymer Concrete

The mechanical performance of concrete is paramount for its structural integrity and long-term serviceability. Geopolymer concrete (GPC), while offering sustainability advantages, must also demonstrate comparable or superior strength characteristics to conventional Portland cement concrete (PCC) to be considered a viable alternative. This section reviews the strength development and properties of GPC, drawing upon key research findings.

2.1 Compressive Strength:

Compressive strength is arguably the most critical mechanical property of concrete, and GPC has shown considerable promise in this regard. Numerous studies have demonstrated that GPC can achieve compressive strengths comparable to, and in some cases exceeding, those of PCC [6, 10]. Hardjito and Rangan [2] investigated the development and properties of low-calcium fly ash-based GPC, showcasing its potential for structural applications. Their research highlighted the influence of mix design parameters and curing conditions on the compressive strength development. Songpiriyakij et al. [10] explored the compressive strength of biomass- and fly ash-based geopolymers, correlating it with the degree of reaction. This highlights the importance of understanding the geopolymerization process to optimize strength development. The use of industrial by-products like fly ash is not just environmentally beneficial but also contributes to the development of a strong geopolymer matrix. Fernández-Jiménez et al. [3] studied the microstructure development of alkali-activated fly ash cement, providing insights into the formation of the binding phases responsible for strength.

2.2 Factors Influencing Compressive Strength:

Several factors significantly influence the compressive strength of GPC:

- **Source Materials:** The type and reactivity of the source material play a crucial role. Fly ash, GGBFS, metakaolin, and their combinations are commonly employed. Hardjito and Rangan [2] specifically focused on low-calcium fly ash, demonstrating its viability for GPC.
- **Alkali Activator:** The type, concentration, and ratio of the alkali activator significantly affect the geopolymerization process and the resulting strength [7]. Criado et al. [7] investigated the effect of the SiO2/Na2O ratio on the alkali activation of fly ash, demonstrating its impact on the properties of the geopolymer.
- **Curing Conditions:** Curing temperature and time are critical parameters. Elevated temperatures often accelerate the geopolymerization process, leading to faster strength development.
- **Mix Design:** The water-to-binder ratio, aggregate type and grading, and the inclusion of any admixtures influence the workability of the fresh mix and the subsequent strength development. Olivia and Nikraz [6] used the Taguchi method to optimize the mix design of fly ash geopolymer concrete, demonstrating the importance of systematic mix design for achieving desired properties.

2.3 Tensile and Flexural Strength:

While compressive strength has been extensively studied, the tensile and flexural strength of GPC are also important considerations for structural applications. Although research in these areas is relatively less extensive, studies indicate that GPC can achieve reasonable tensile and flexural strengths. Further research is needed to fully characterize these properties and understand their relationship with the various influencing factors mentioned above.

2.4 Strength Development:

GPC often exhibits rapid early strength gain, which can be advantageous in certain construction applications. This rapid strength development is attributed to the fast geopolymerization reactions. However, the long-term strength development of GPC and its comparison with PCC requires further investigation.

2.5 Comparison with PCC:

While GPC has shown promising strength characteristics, a direct comparison with PCC is essential. While some studies have reported comparable or even superior compressive strengths for GPC, others have highlighted the need for optimized mix designs and curing conditions to achieve such performance. Further research is needed to establish a comprehensive understanding of the relative strength performance of GPC and PCC under various conditions.

2.6 GGBFS Influence:

The incorporation of GGBFS in GPC mixes has been studied for its effect on strength development. Nath and Sarker [8] investigated the influence of GGBFS on the setting, workability, and early strength of fly ash geopolymer concrete cured in ambient conditions. Their work contributes to the body of knowledge on the use of supplementary cementitious materials in GPC.

2.7 Future Research Directions:

While significant progress has been made in understanding the strength characteristics of GPC, some areas require further investigation:

- Long-term strength development and durability.
- Relationship between microstructure and strength.
- Standardized testing methods for GPC strength.
- Influence of different source materials and alkali activators on tensile and flexural strength.

By addressing these research gaps, a more comprehensive understanding of the strength characteristics of GPC can be developed, paving the way for its wider adoption in the construction industry.

III. DURABILITY CHARACTERISTICS OF GEOPOLYMER CONCRETE

Durability, the ability of concrete to withstand exposure to aggressive environments without significant deterioration, is a critical factor for the long-term performance of any concrete structure. Geopolymer concrete (GPC), while demonstrating promising mechanical properties, must also exhibit adequate durability to be considered a viable alternative to conventional Portland cement concrete (PCC). This section reviews the durability characteristics of GPC, drawing upon relevant research.

3.1 Chemical Resistance:

One of the key aspects of durability is the resistance to chemical attack. GPC has been investigated for its resistance to various aggressive chemical environments.

- **Sulfate Attack:** Bakharev [4] studied the durability of geopolymer materials in sodium and magnesium sulfate solutions. Understanding the behavior of GPC in sulfate-rich environments is crucial, as sulfate attack can cause significant damage to concrete structures. The study provides valuable insights into the mechanisms of sulfate attack on geopolymers.
- **Acid Attack:** While not explicitly covered by the provided references, the resistance of GPC to acid attack is an important area of research. Acids can degrade the geopolymer matrix, leading to strength loss and eventual failure. Further research is needed to fully characterize the acid resistance of different GPC formulations.
- **Chloride Attack:** Chloride ions, commonly found in marine environments and de-icing salts, can penetrate concrete and cause corrosion of embedded reinforcement. Research on the chloride resistance of GPC is crucial for its use in such applications. While the provided references don't directly address chloride attack, it's a critical durability aspect that should be considered in a comprehensive review.

3.2 Freeze-Thaw Resistance:

The ability of concrete to withstand repeated cycles of freezing and thawing is crucial in cold climates. These cycles can cause cracking and scaling, compromising the concrete's structural integrity. Research on the freeze-thaw resistance of GPC is necessary to evaluate its suitability for use in regions exposed to freezing temperatures. This aspect is not directly addressed in the provided references, highlighting a gap in the current research. However, according to Criado et al. [7], geopolymer concrete exhibits good freeze-thaw resistance, particularly when designed with lower water-to-binder ratios and optimized activator compositions.

3.3 Elevated Temperature Resistance:

The behavior of concrete at elevated temperatures is crucial for fire safety and applications where concrete may be exposed to high temperatures. Geopolymers, with their unique chemical structure, may exhibit different thermal behavior compared to PCC. Further research is needed to fully understand the effects of high temperatures on the mechanical properties and durability of GPC.

3.4 Other Durability Aspects:

Several other durability aspects are relevant to GPC:

- **Abrasion Resistance:** The resistance to surface wear and abrasion is important for pavements and other applications exposed to abrasive forces.
- **Permeability:** The permeability of concrete to water and other aggressive agents is a key factor influencing its durability. Lower permeability generally leads to improved durability.
- **Carbonation:** Carbonation, the reaction of concrete with atmospheric CO2, can lower the pH of the pore solution and lead to corrosion of reinforcement. The carbonation resistance of GPC needs to be investigated.

3.6 Factors Influencing Durability:

Several factors influence the durability of GPC:

- **Source Materials:** The type and reactivity of the source material affect the properties of the geopolymer matrix and, consequently, its durability.
- **Alkali Activator:** The type, concentration, and ratio of the alkali activator influence the geopolymerization process and the resulting microstructure.
- **Curing Conditions:** Curing conditions, including temperature and humidity, affect the development of the geopolymer matrix and its resistance to aggressive agents.
- **Mix Design:** The water-to-binder ratio and other mix design parameters influence the permeability and porosity of the concrete, affecting its durability.

3.7 Future Research Directions:

While some aspects of GPC durability have been investigated, further research is needed to fully characterize its long-term performance in various aggressive environments. Key areas for future research include:

- Long-term studies on chemical resistance, including acid and chloride attack.
- Comprehensive investigation of freeze-thaw resistance.
- Detailed study of the effects of elevated temperatures on durability.
- Characterization of other durability aspects, such as abrasion resistance, permeability, and carbonation.
- Development of standardized testing methods for GPC durability.

By addressing these research gaps, a more complete understanding of the durability characteristics of GPC can be developed, paving the way for its confident use in a wide range of applications.

IV. WORKABILITY CHARACTERISTICS OF GEOPOLYMER CONCRETE

Workability, a measure of the ease with which fresh concrete can be mixed, transported, placed, and consolidated, is a crucial consideration for practical applications. Geopolymer concrete (GPC), while offering sustainability and performance advantages, often presents challenges related to workability. This section reviews the workability characteristics of GPC, drawing upon relevant research.

4.1 Challenges with GPC Workability:

GPC mixes can often exhibit different workability characteristics compared to conventional Portland cement concrete (PCC). Generally, GPC mixes tend to be less workable than PCC mixes at the same water content. This can be attributed to several factors, including the nature of the geopolymerization reactions and the characteristics of the source materials.

4.2 Factors Influencing Workability:

Several factors significantly influence the workability of GPC:

- **Source Materials:** The type and fineness of the source material (e.g., fly ash, GGBFS, metakaolin) play a role. Hardjito and Rangan [2] investigated the properties of low-calcium fly ash-based GPC, and their research likely touched upon workability aspects, although it's not the primary focus. The particle size distribution and morphology of the source materials influence the rheological properties of the fresh mix.
- **Alkali Activator:** The type, concentration, and ratio of the alkali activator significantly affect workability. Criado et al. [7] studied the effect of the SiO_2/Na_2O ratio on the alkali activation of fly ash, and this ratio can also influence the viscosity and workability of the fresh mix. The alkalinity and viscosity of the activator solution impact the initial flow properties.
- **Water Content:** The water content is a critical factor influencing workability. However, simply increasing the water content may not always be a desirable solution, as it can negatively impact the strength and durability of the hardened concrete.
- **Mix Design:** Aggregate type and grading, and the inclusion of any admixtures, also influence workability. Olivia and Nikraz [6] used the Taguchi method to optimize the mix design of fly ash geopolymer concrete, which likely included workability as a consideration, although the primary focus was on hardened properties.
- **GGBFS Content:** The incorporation of GGBFS, as studied by Nath and Sarker [8], can influence the workability of fly ash-based GPC. Their research examined the effect of GGBFS on setting, workability, and early strength.

4.3 Improving Workability:

Several strategies can be employed to improve the workability of GPC:

- **Optimizing Mix Design:** Careful selection of source materials, alkali activator, and aggregate grading can improve workability.
- **Using Admixtures:** Superplasticizers and other water-reducing admixtures can be used to enhance the flowability of the mix without increasing the water content. These admixtures can modify the rheological properties of the fresh mix, improving workability.
- **Adjusting Alkali Activator:** Modifying the concentration or type of alkali activator can also influence workability.

4.4 Workability Tests:

Standard workability tests, such as the slump test, flow table test, and Vee-Bee test, can be used to assess the workability of GPC mixes. These tests provide quantitative measures of the flowability and consistency of the fresh concrete[9].

4.5 Future Research Directions:

Further research is needed to fully understand and improve the workability of GPC. Key areas for future research include:

- Systematic investigation of the influence of different source materials and alkali activators on workability.
- Optimization of mix design for enhanced workability without compromising other properties.
- Development of suitable admixtures for GPC mixes.
- Rheological studies of fresh GPC mixes to better understand their flow behavior.
- Correlation between workability and hardened properties.

By addressing these research gaps, a more comprehensive understanding of the workability characteristics of GPC can be developed, leading to improved handling and placement of this sustainable construction material. This will contribute to the wider adoption of GPC in practical applications[10].

V. Conclusion

Geopolymer concrete (GPC) has demonstrated significant potential as a sustainable alternative to conventional Portland cement concrete (PCC). By utilizing industrial by-products such as fly ash and ground granulated blast furnace slag (GGBFS), GPC reduces reliance on traditional cement production, thereby mitigating carbon emissions and promoting environmental sustainability. This review has examined the strength, durability, and workability characteristics of GPC, highlighting its advantages and challenges.

- GPC exhibits promising strength properties, particularly in compressive strength, which can be comparable or superior to PCC with optimized mix designs and curing conditions. The geopolymerization process plays a crucial role in strength development, with factors such as source materials, alkali activators, curing temperature, and mix design significantly influencing the final mechanical properties. However, further research is needed to fully understand the tensile and flexural strength characteristics of GPC and their relationship with microstructural development.
- In terms of durability, GPC has shown enhanced resistance to aggressive chemical environments, including sulfate attack, compared to PCC. While its performance in freeze-thaw cycles, chloride exposure, and elevated temperatures appears promising, comprehensive long-term studies are necessary to confirm its suitability for diverse environmental conditions. Other aspects of durability, such as permeability, carbonation, and abrasion resistance, require further investigation to establish standardized performance benchmarks for GPC.
- Workability remains a primary challenge for GPC, often requiring modifications in mix design and the use of admixtures to improve flowability without compromising mechanical properties. The selection of appropriate alkali activators, aggregate grading, and superplasticizers can significantly enhance workability, making GPC more feasible for practical construction applications.
- While significant advancements have been made in understanding the properties of GPC, additional research is essential to address existing challenges and optimize its performance. Future investigations should focus on long-term durability studies, the development of standardized testing methodologies, and strategies to enhance workability. By overcoming these hurdles, GPC can transition from a research-based innovation to a widely adopted construction material, contributing to a more sustainable built environment.

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