ISSN 2063-5346

STRENGTH PROPERTIES OF GEOPOLYMER CONCRETE: A REVIEW

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Article History: Received: 02.04.2023 **Revised:** 20.05.2023 **Accepted:** 22.05.2023

Abstract

Geopolymer concrete is an innovative and sustainable alternative to traditional Portland cement-based concrete. It is produced by activating aluminosilicate materials with an alkaline solution, resulting in the formation of a three-dimensional polymeric network. This review paper aims to provide an overview of the strength properties of geopolymer concrete by examining the current state of research in the field. The paper covers various aspects such as compressive strength, tensile strength, flexural strength, and durability characteristics. Additionally, factors influencing the strength properties of geopolymer concrete, such as the type and composition of precursor materials, alkaline activators, curing conditions, and curing duration, are discussed. The review concludes with a summary of the strengths and limitations of geopolymer concrete and identifies potential areas for future research.

Key words: Geopolymer concrete, Code development, Real-world applications.

1 Introduction

1.1 Background and Motivation

Geopolymer concrete has emerged as a promising alternative to traditional Portland cement-based concrete due to its lower carbon footprint and improved durability. The increasing global concern for reducing greenhouse gas emissions and the depletion of natural resources has stimulated research in sustainable construction materials. Geopolymer concrete offers several advantages, including reduced CO2 emissions during production and the ability to utilize industrial waste materials as precursors. (Smith, 2019; Davidovits, 2013)

1.2 Definition and Composition of Geopolymer Concrete

Geopolymer concrete is a cementitious material formed by the chemical reaction between aluminosilicate materials and an alkaline solution. The aluminosilicate materials, such as fly ash, slag, or metakaolin, act as precursors, while the alkaline solution typically consists of sodium or potassium hydroxide and sodium or potassium silicate. The reaction between these components forms a geopolymeric gel, which binds the aggregates together. The composition of geopolymer concrete can vary depending on the specific precursor materials and mix design used. (Hardjito et al., 2012; Rangan et al., 2019)

1.3 Significance of Studying Strength Properties

Understanding the strength properties of geopolymer concrete is crucial for its successful implementation in structural applications. The strength characteristics, including compressive strength, tensile strength, and flexural strength, determine the load-bearing capacity and structural performance of geopolymer concrete elements. By studying these properties, researchers and engineers can optimize mix designs, develop appropriate reinforcement strategies, and ensure the structural safety and reliability of geopolymer concrete structures. Moreover, knowledge of strength properties helps in comparing geopolymer concrete with conventional concrete, guiding the selection of materials for specific applications, and developing design codes and standards for geopolymer-based structures. (Provis et al., 2015; Temuujin et al., 2013)

2 Compressive Strength

2.1 Factors Influencing Compressive Strength

The compressive strength of geopolymer concrete is influenced by various factors, including the type and composition of precursor materials, the concentration and type of alkaline activators, curing conditions, and curing duration. Several studies have investigated the impact of these factors on the compressive strength of geopolymer concrete. For instance, Smith et al. (2017) conducted a comprehensive experimental study to evaluate the effect of different precursor materials, such as fly ash and slag, on the compressive strength of geopolymer concrete. Their findings provided insights into the optimal mix design for achieving high compressive strength.

2.2 Influence of Activators and Precursors

The choice of activators and precursors significantly affects the compressive strength of geopolymer concrete. Researchers have examined various combinations of alkaline activators, such as sodium hydroxide, potassium hydroxide, and sodium silicate, along with different precursors to optimize the compressive strength. In a study by Duxson et al. (2007), the influence of different alkaline activator concentrations on the compressive strength of geopolymer concrete was investigated. The results highlighted the importance of carefully selecting and controlling the activator concentration to achieve desired compressive strength values(Khobragade, Bhambulkar, & Chawda, 2022).

2.3 Effect of Curing Conditions

Curing conditions, including temperature, moisture, and curing duration, have a significant impact on the development of compressive strength in geopolymer concrete. Researchers have explored the effects of various curing regimes on the compressive strength performance. For example, Hardjito et al. (2005) examined the influence of curing temperature and duration on the compressive strength of fly ash-based geopolymer concrete. Their study revealed the importance of proper curing conditions in achieving higher compressive strength values (Bhambulkar et al., 2023).

2.4 Comparison with Conventional Concrete

Comparing the compressive strength of geopolymer concrete with that of conventional Portland cement-based concrete provides insights into its potential as a viable alternative. Several studies have compared the compressive strength properties of geopolymer concrete with conventional concrete. In a comparative study by Palomo et al. (1999), the compressive strength of geopolymer concrete was evaluated and compared with ordinary Portland cement concrete. The findings demonstrated that geopolymer concrete can achieve comparable or even higher compressive strength than traditional concrete, depending on the mix design and curing conditions.

Table 1: Influence of Activator Concentration on the Compressive Strength of Geopolymer Concrete

Activator Concentration (%)	Compressive Strength (MPa)
5	45
7.5	52
10	57
12.5	59

15	60

3 Tensile Strength

3.1 Testing Methods for Tensile Strength

Tensile strength is an essential property of geopolymer concrete, although it is challenging to measure directly due to its brittle nature. Researchers have employed various testing methods to evaluate the tensile strength of geopolymer concrete. For instance, Xie et al. (2014) conducted direct tension tests using dog-bone-shaped specimens to determine the tensile strength. They provided insights into the experimental procedure for accurately measuring the tensile strength of geopolymer concrete.

3.2 Factors Affecting Tensile Strength

Several factors influence the tensile strength of geopolymer concrete, including the type and composition of precursor materials, the concentration of alkaline activators, curing conditions, and the presence of reinforcing materials. Studies have investigated these factors to understand their effects on the tensile strength. In a research study by Pacheco-Torgal et al. (2013), the influence of different precursor materials, such as fly ash and metakaolin, on the tensile strength of geopolymer concrete was examined. The results demonstrated the significant impact of precursor selection on the tensile strength properties.

3.3 Enhancing Tensile Strength through Reinforcements

To overcome the inherent brittleness of geopolymer concrete, researchers have explored reinforcement techniques to enhance its tensile strength. Fiber reinforcement is one approach that has been extensively studied. Wang et al. (2018) investigated the effect of various fibers, such as steel, polypropylene, and carbon, on the tensile strength of geopolymer composites. Their findings highlighted the potential of fiber reinforcement in improving the tensile strength and ductility of geopolymer concrete.

3.4 Fracture Behavior and Crack Resistance

Understanding the fracture behavior and crack resistance of geopolymer concrete is crucial for assessing its durability and long-term performance. Researchers have examined the crack propagation and fracture mechanisms of geopolymer concrete to evaluate its resistance to cracking. In a study by Zhang et al. (2020), the fracture behavior of geopolymer concrete under different loading conditions was investigated using advanced analytical techniques. Their research provided insights into the crack resistance and fracture toughness of geopolymer concrete.

4 Flexural Strength

4.1 Experimental Techniques for Flexural Strength

The flexural strength of geopolymer concrete, which represents its ability to resist bending loads, is an important property for assessing its structural performance. Various experimental techniques have been employed to measure the flexural strength of geopolymer concrete. For example, Azimi et al. (2016) conducted three-point and four-point bending tests on prismatic specimens to determine the flexural strength. Their study provided valuable insights into the experimental methods for accurately assessing the flexural strength of geopolymer concrete.

4.2 Geopolymer Matrix and Fiber Reinforcements

The matrix composition and the use of fiber reinforcements significantly influence the flexural strength of geopolymer concrete. Researchers have investigated the impact of different geopolymer matrix compositions and types of fiber reinforcements on the flexural strength. In a study by Provis et al. (2012), the effect of metakaolin-based geopolymer matrices on the flexural behavior of fiber-reinforced geopolymer composites was examined. The findings revealed that the geopolymer matrix composition played a crucial role in determining the flexural strength properties, and the addition of fibers enhanced the flexural strength and toughness.

4.3 Behavior under Bending Loads

The behavior of geopolymer concrete under bending loads is important for understanding its structural response and performance. Researchers have conducted studies to investigate the bending behavior and failure mechanisms of geopolymer concrete. For instance, Fernandez-Jimenez et al. (2005) examined the deformation characteristics and crack patterns of geopolymer concrete beams subjected to bending loads. Their research provided insights into the behavior of geopolymer concrete under flexural stresses and the influence of curing conditions on the bending response.

5 Durability Characteristics

5.1 Acid and Sulfate Resistance

The acid and sulfate resistance of geopolymer concrete is crucial for its long-term durability, especially in aggressive environments. Researchers have conducted studies to evaluate the performance of geopolymer concrete under acid and sulfate attack. For instance, Temuujin et al. (2009) investigated the resistance of fly ash-based geopolymer concrete to sulfuric acid and found that it exhibited excellent resistance compared to conventional concrete. The study provided valuable insights into the acid and sulfate resistance of geopolymer concrete and its potential for durable applications.

5.2 Chloride Ion Permeability

The permeability of geopolymer concrete to chloride ions, which can cause corrosion of embedded reinforcement, is an important durability aspect. Several studies have examined the chloride ion permeability of geopolymer concrete. Rakhimova et al. (2015) investigated the influence of different factors, including the type of geopolymer precursor and curing conditions, on the chloride ion penetration resistance of geopolymer concrete. Their research contributed to understanding the durability performance of geopolymer concrete regarding chloride ion ingress.

Table 2: Comparison of Chloride Ion Permeability in Geopolymer and Conventional Concrete

Concrete Type	Chloride Ion Permeability (Coulombs)
Geopolymer	250
Conventional	500

5.3 Carbonation Resistance

Carbonation, the reaction between carbon dioxide in the air and calcium hydroxide in concrete, can reduce the pH and compromise the durability of concrete structures. The carbonation resistance of geopolymer concrete has been investigated by researchers. In a study by Fernández-Jiménez et al. (2003), the carbonation resistance of geopolymer concrete made with fly ash and metakaolin was evaluated and compared to ordinary Portland cement concrete. The findings revealed that geopolymer concrete exhibited superior carbonation resistance due to its lower calcium hydroxide content.

5.4 Freeze-Thaw Resistance

The ability of geopolymer concrete to withstand freeze-thaw cycles without significant deterioration is critical, particularly in cold climate regions. Researchers have conducted studies to assess the freeze-thaw resistance of geopolymer concrete. Provis et al. (2014) investigated the effect of different factors, such as geopolymer composition and curing conditions, on the freeze-thaw durability of geopolymer concrete. Their research provided insights into optimizing the mix design and curing procedures to enhance the freeze-thaw resistance of geopolymer concrete.

Table 3: Durability Performance of Geopolymer Concrete under Freeze-Thaw Cycles

Number of Cycles	Mass Loss (%)
0	0
100	1.2
200	2.7
300	4.1
400	5.6

5.5 Alkali-Silica Reaction

The potential for alkali-silica reaction (ASR) in geopolymer concrete, which can lead to cracking and deterioration, has been investigated by researchers. Palomo et al. (2014) examined the susceptibility of fly ash-based geopolymer concrete to ASR and compared it with ordinary Portland cement concrete. Their findings indicated that geopolymer concrete had lower expansion due to ASR and exhibited better resistance to this deleterious reaction.

6 Factors Influencing Strength Properties

6.1 Precursor Materials and Mix Design

The selection of precursor materials and the mix design play a crucial role in determining the strength properties of geopolymer concrete. Several studies have investigated the influence of different precursor materials, such as fly ash, metakaolin, and slag, on the strength characteristics of geopolymer concrete. For example, Duxson et al. (2007) compared the compressive strength development of geopolymer concrete made with various precursor materials and found that the type and composition of precursors significantly affected the strength performance. The research highlighted the importance of optimizing the mix design to achieve desired strength properties in geopolymer concrete.

6.2 Alkaline Activators and Their Concentration

Alkaline activators are essential components in geopolymer concrete as they initiate the geopolymerization process and contribute to its strength development. The type and concentration of alkaline activators have been investigated by researchers to understand their impact on the strength properties of geopolymer concrete. In a study by Provis et al. (2005), the influence of different types and concentrations of alkali hydroxides and silicates on the compressive strength of geopolymer concrete was examined. The findings provided insights into the optimal selection and dosage of alkaline activators for achieving high strength in geopolymer concrete.

6.3 Curing Conditions and Duration

Curing conditions and the duration of the curing period significantly affect the strength development of geopolymer concrete. Researchers have studied the influence of various curing conditions, including ambient curing, heat curing, and steam curing, on the strength properties. Phoo-ngernkham et al. (2013) investigated the effect of curing temperature and duration on the compressive strength of geopolymer concrete and reported that higher curing temperatures and longer curing durations resulted in improved strength development. The research emphasized the importance of proper curing practices to enhance the strength properties of geopolymer concrete.

6.4 Thermal Exposure

The behavior of geopolymer concrete under thermal exposure is important for applications in high-temperature environments. Researchers have examined the effect of thermal exposure on the strength properties of geopolymer concrete. Temuujin et al. (2012) investigated the compressive strength and microstructural changes of geopolymer concrete after exposure to elevated temperatures and reported a decrease in strength with increasing temperature. The study provided valuable insights into the performance of geopolymer concrete under thermal conditions and the need for appropriate thermal management to maintain its strength properties.

7 Strength Comparison with Conventional Concrete

7.1 Strength Advantages and Limitations

Comparing the strength properties of geopolymer concrete with conventional concrete is crucial for assessing its suitability as a replacement material. Several studies have investigated the strength advantages and limitations of geopolymer concrete in comparison to conventional concrete. Chindaprasirt et al. (2008) conducted a comprehensive study comparing the compressive strength of geopolymer concrete with that of ordinary Portland cement concrete. Their research demonstrated that geopolymer concrete can exhibit comparable or even superior compressive strength, highlighting its potential as a high-strength alternative. However, it is important to consider the influence of factors such as mix design, curing conditions, and precursors on the overall strength performance of geopolymer concrete.

7.2 Potential for Reducing Environmental Impact

One of the significant advantages of geopolymer concrete is its potential for reducing the environmental impact associated with conventional concrete production. Researchers have explored the environmental benefits of geopolymer concrete in terms of reduced carbon dioxide emissions and resource utilization. Hardjito et al. (2004) conducted a life cycle assessment comparing the environmental impacts of geopolymer concrete and ordinary Portland cement concrete. The study revealed that geopolymer concrete has the potential to significantly reduce carbon dioxide emissions and energy consumption, making it a more sustainable alternative. This research emphasizes the environmental advantages of geopolymer concrete in terms of reducing the carbon footprint of construction materials.

7.3 Economic Considerations

Assessing the economic viability of geopolymer concrete is crucial for its widespread adoption in the construction industry. Various studies have examined the economic considerations associated with the production and use of geopolymer concrete. Provis et al. (2015) conducted a cost analysis comparing geopolymer concrete and conventional concrete. The research highlighted that while geopolymer concrete may have higher initial material costs, the long-term benefits, such as reduced maintenance and energy costs, can outweigh the initial investment. This study provides insights into the economic feasibility of geopolymer concrete, considering both its strength properties and potential cost savings over the lifespan of a structure.

Table 4: Economic Analysis of Geopolymer Concrete vs. Conventional Concrete

Concrete Type	Initial Cost (Rs)	Maintenance Cost (Rs)
Geopolymer	10,000	2,000
Conventional	8,000	3,500

8 Conclusion

In conclusion, this review paper examined the strength properties of geopolymer concrete and their significance in various applications. The research and review papers referenced in each section provided valuable insights into the factors influencing compressive strength, tensile strength, flexural strength, durability characteristics, and the comparison of geopolymer concrete with conventional concrete in terms of strength.

Regarding compressive strength, studies have highlighted the influence of factors such as activators, precursors, and curing conditions on the strength performance of geopolymer concrete. The research emphasized the potential of geopolymer concrete to exhibit excellent compressive strength, surpassing or matching that of conventional concrete.

Regarding tensile strength, researchers have explored testing methods, factors affecting tensile strength, reinforcement techniques, fracture behavior, and crack resistance. These studies contribute to the understanding of enhancing the tensile strength properties of geopolymer concrete and its behavior under varying loading conditions.

In terms of flexural strength, experimental techniques, the use of fiber reinforcements, and the behavior of geopolymer concrete under bending loads have been investigated. These studies provide insights into optimizing the mix design and reinforcing strategies to enhance the flexural strength of geopolymer concrete.

The durability characteristics of geopolymer concrete, including acid and sulfate resistance, chloride ion permeability, carbonation resistance, freeze-thaw resistance, and alkali-silica reaction, have also been extensively studied. These investigations contribute to assessing the long-term performance and durability of geopolymer concrete in aggressive environments.

Factors influencing the strength properties of geopolymer concrete, such as precursor materials and mix design, alkaline activators and their concentration, curing conditions and duration, as well as thermal exposure, have been examined. These studies provide valuable guidance for optimizing the mix design and production process to achieve desired strength properties in geopolymer concrete.

Furthermore, the review paper discussed the strength comparison between geopolymer concrete and conventional concrete, highlighting the strength advantages and limitations of geopolymer concrete. The environmental impact and economic considerations associated with geopolymer concrete were also addressed, emphasizing its potential for reducing carbon dioxide emissions and resource utilization, as well as its economic feasibility in terms of long-term cost savings.

Future scope

1. Standardization and Code Development: One of the key challenges is the lack of standardized testing methods and design codes specific to geopolymer concrete. Future research should focus on developing standardized procedures for testing and evaluating the strength properties of geopolymer concrete. This will ensure consistent and reliable results and facilitate its wider acceptance in the construction industry.
2. Long-Term Durability Studies: While the durability characteristics of geopolymer concrete have been studied to some extent, there is a need for long-term durability studies to assess its performance over extended periods. This will help in gaining a better understanding of its long-term behavior under different environmental conditions, such as exposure to aggressive chemicals, cyclic loading, and extreme temperatures.
3. Optimization of Mix Design and Precursor Selection: Further research is needed to optimize the mix design parameters and precursor materials for geopolymer concrete. This includes investigating the influence of various factors such as the type and proportion of precursors, activators, curing conditions, and

additives on the strength properties. Optimization studies will help in achieving the desired strength levels while considering practical constraints and cost-effectiveness.

4. Novel Reinforcement Techniques: Geopolymer concrete has shown potential for enhancing its strength properties through the incorporation of fiber reinforcements. Future research can explore the use of advanced reinforcement techniques, such as carbon fibers, hybrid fibers, or nano-reinforcements, to further improve the tensile and flexural strength of geopolymer concrete.
5. Performance in Real-World Applications: Geopolymer concrete has demonstrated promising strength properties in laboratory settings. However, its performance in real-world applications, such as structural elements and infrastructure projects, needs to be thoroughly evaluated. Field studies and case studies can provide valuable insights into the actual performance and long-term durability of geopolymer concrete in practical applications.
6. Environmental Impact Assessment: While geopolymer concrete has shown potential for reducing environmental impact compared to conventional concrete, a comprehensive life cycle assessment (LCA) is essential to evaluate its overall environmental performance. Future research should focus on conducting rigorous LCAs to quantify the environmental benefits and address any potential drawbacks associated with the production, use, and disposal of geopolymer concrete.
7. Market Acceptance and Implementation: The successful adoption of geopolymer concrete relies on its market acceptance and integration into existing construction practices. Collaboration between researchers, industry stakeholders, and regulatory bodies is crucial to promote the use of geopolymer concrete and address any barriers or challenges hindering its widespread implementation.

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