A Comprehensive Review on the Durability Performance of Geopolymer Concrete

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1. Abstract

Geopolymer concrete (GPC) has emerged as a sustainable alternative to Ordinary Portland Cement (OPC) concrete due to its lower carbon footprint, reduced energy consumption, and utilization of industrial by-products. It is synthesized through the alkaline activation of aluminosilicate materials such as fly ash, metakaolin, and ground granulated blast furnace slag, resulting in a three-dimensional polymeric network. In recent years, research interest has increasingly focused on the durability performance of geopolymer concrete under aggressive environmental conditions. This review paper presents a comprehensive evaluation of the durability characteristics of geopolymer concrete, including resistance to elevated temperatures, chemical attack, chloride ion penetration, abrasion, and long-term strength development. The influence of alkaline activators, curing regimes, precursor materials, and the incorporation of mineral admixtures and fibers on durability is critically discussed. The review highlights that geopolymer concrete exhibits superior resistance to acid and sulfate attack, low chloride permeability, and improved thermal stability compared to OPC concrete. Based on current findings, geopolymer concrete is identified as a promising and durable construction material suitable for sustainable infrastructure development.

Keywords: Geopolymer concrete; alkaline activator; aluminosilicate materials; durability;chemical resistance; sustainability.

1. Introduction

The construction industry is one of the largest contributors to global carbon dioxide emissions, primarily due to the extensive use of Ordinary Portland Cement (OPC). The manufacture of OPC involves high-temperature clinker production, resulting in significant energy consumption and greenhouse gas emissions. In response to increasing environmental concerns and sustainability goals, alternative cementitious materials have been developed, among which geopolymer concrete has gained substantial attention. Geopolymer concrete is an inorganic polymer formed by the reaction of aluminosilicate-rich materials with alkaline activators. Unlike OPC hydration, geopolymerization involves dissolution, transportation, and polycondensation of alumina and silica species, leading to the formation of a rigid and stable polymeric network. The use of industrial by-products such as fly ash and slag not only reduces environmental pollution but also enhances resource efficiency. While the mechanical properties of geopolymer concrete have been extensively studied, its long-term durability remains a critical factor for widespread adoption in structural applications. Durability governs the service life of concrete structures, particularly in aggressive environments such as marine exposure, industrial zones, and high-temperature conditions. This review aims to critically assess the durability related performance of geopolymer concrete and compare it with conventional OPC-based concrete.

2. Materials Concrete Used in Geopolymer Concrete

2.1 Aluminosilicate Source Materials

The primary source materials for geopolymer concrete are aluminosilicate-rich industrial by-products and natural minerals. Commonly used materials include: - Fly ash (Class F and Class C): Widely used due to its high silica and alumina content and spherical particle shape, which improves workability. - Metakaolin: A highly reactive calcined clay that enhances early strength and microstructural densification. - Ground Granulated Blast Furnace Slag (GGBS): Provides calcium content, contributing to faster setting and improved early strength.

2.2 Alkaline Activators

Alkaline activators play a crucial role in initiating the geopolymerization process. Typically, a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) with sodium silicate or potassium silicate solutions is used. The concentration, silicate-to-hydroxide ratio, and type of alkali significantly influence the reaction kinetics and final properties of geopolymer concrete

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3. Geopolymerization Mechanism

The geopolymerization process consists of three main stages: dissolution of aluminosilicate materials in an alkaline medium, transportation and orientation of dissolved species, and polycondensation to form a three-dimensional network. This covalently bonded structure imparts high strength and chemical stability to geopolymer concrete. The absence of calcium hydroxide, which is vulnerable to chemical attack in OPC systems, is a key factor contributing to improved durability.

4. Durability Properties of Geopolymer Concrete

4.1 Resistance to Elevated Temperature

Geopolymer concrete demonstrates superior performance at elevated temperatures compared to OPC concrete. Studies have shown that geopolymer concrete retains significant compressive strength when exposed to temperatures up to 600–800°C, attributed to its ceramic-like structure and low calcium content. Optimal curing temperatures further enhance thermal resistance.

4.2 Chloride Ion Penetrability

Low chloride ion penetration is essential for reinforced concrete structures exposed to marine environments. Geopolymer concrete generally exhibits low to moderate chloride permeability due to its dense microstructure and refined pore system. This improves resistance to reinforcement corrosion.

4.3 Acid and Sulfate Resistance

Geopolymer concrete shows excellent resistance to acid and sulfate attack compared to OPC concrete. The absence of calcium hydroxide minimizes the formation of expansive reaction products, resulting in lower mass loss and reduced strength degradation in acidic environments.

4.4 Abrasion and Wear Resistance

Abrasion resistance is critical for industrial floors and pavements. Geopolymer concrete has demonstrated comparable or superior abrasion resistance relative to OPC concrete, particularly when reinforced with fibers or micro-fillers.

5. Effect of Additives and Fibers on Durability

The incorporation of supplementary materials such as micro-silica, nano-silica, and fibers significantly enhances the durability of geopolymer concrete. Polypropylene, steel, and basalt fibers improve crack resistance, toughness, and abrasion resistance. Micro-silica contributes to pore refinement and increased chemical resistance.

6. Comparison with OPC Concrete

Compared to OPC concrete, geopolymer concrete offers superior resistance to chemical attack, lower permeability, and better performance at high temperatures. Although OPC concrete may show faster early-age strength under ambient curing, geopolymer concrete provides better long-term durability and sustainability benefits.

7. Challenges and Research Gaps

Despite its advantages, geopolymer concrete faces challenges related to variability of source materials, lack of standardized mix design procedures, and limited long-term field performance data. Further research is required to develop design codes, improve ambient curing performance, and assess lifecycle durability.

8. Future Scope

Future research should focus on large-scale field applications, durability modeling, and the development of hybrid geopolymer systems. The use of locally available waste materials and low-alkali activators can further enhance sustainability and economic feasibility.

9. Conclusions

This review highlights that geopolymer concrete is a durable and sustainable alternative to OPC concrete. Its superior resistance to heat, chemical attack, chloride penetration, and abrasion makes it suitable for aggressive environmental conditions. With continued research and standardization, geopolymer concrete has strong potential for widespread adoption in the construction industry.

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