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Study on the Performance and Carbon Emission of Geopolymers Concrete

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Abstract. As the global demand for reducing carbon emissions increases, the construction industry must seek environmentally friendly alternative materials. Geopolymers concrete, as a low-carbon and environmentally friendly material, has emerged as a potential alternative to cement concrete due to its excellent mechanical properties and environmental adaptability. This paper focuses on geopolymers concrete, exploring its applications, mechanical properties, and carbon emissions. Firstly, the composition, reaction mechanism and application prospect of geopolymers concrete are systematically analyzed. Then, the mechanical properties of cement concrete are studied, and its superior compressive strength, high temperature resistance and corrosion resistance compared with traditional cement concrete are highlighted. Finally, the carbon emissions in the production process are discussed in detail, and the effects of different raw materials and production methods on carbon emissions are compared. It is shown that the carbon emissions of geopolymers concrete are significantly lower than that of traditional cement concrete. The research concludes that geopolymers concrete not only has significant environmental benefits but also possesses strong mechanical properties and excellent durability, showing great potential for applications in green buildings, marine engineering, and refractory materials. In the future, by reducing production costs, optimizing processes, and promoting standardization, geopolymers concrete is expected to become an important green material in the construction industry, contributing to the achievement of global carbon reduction goals.

Keywords: Geopolymers; Concrete; Mechanical properties; Carbon emissions; Construction applications.

1. Introduction

In the context of rapid urbanization, concrete is widely used as a global construction material. However, its excessive use has had a significant impact on environmental issues worldwide. The environmental impact of concrete primarily comes from cement. In global carbon dioxide emissions, cement alone accounts for 8%, consumes 12-15% of industrial energy, and for every 10 kilograms of cement produced, nearly 9 kilograms of carbon dioxide are emitted [1-3]. In concrete production, 65-75% of greenhouse gases are generated during the cement manufacturing process. [4]. Therefore, finding alternatives to cement in concrete is necessary to reduce carbon emissions while maintaining good performance. One important alternative is geopolymers concrete, which uses alkali-activated binders instead of ordinary Portland cement. It has lower carbon emissions and superior performance compared to traditional concrete.

Geopolymers are inorganic polymer materials. They can be synthesized using natural materials and industrial waste products, activated by alkali or acid reactions. Studies show that geopolymers have properties such as high-temperature resistance, corrosion resistance, good stability, and durability [5, 6], offering promising prospects for development and application in building materials and high-temperature resistant materials.

In the context of large-scale modern urban construction, industrial hazardous solid wastes such as fly ash, slag, and red mud are discharged in large quantities, causing water, soil, and air pollution, raising public concerns. The application of geopolymers materials offers effective solutions, as they can use solid waste as raw materials, reducing solid waste emissions; on the other hand, they can reduce the dependence on natural resources. This paper aims to analyze the performance and carbon emissions of geopolymers concrete, providing theoretical support for the development of global green buildings.

2. Geopolymers

2.1. Overview

Geopolymers, a class of inorganic materials, were first proposed and named by Professor Joseph Davidovits [7]. This material is an amorphous three-dimensional network structure, and gelation of reactive aluminosilicate minerals or industrial aluminosilicate waste in a strong alkali solution at room or high temperatures. The widespread adoption of geopolymers is due to their ability to utilize industrial solid wastes, such as red mud, blast furnace slag, fly ash, recycled clay bricks, metakaolin, mine tailings, ceramic waste, and glass, converting them into resources while significantly reducing CO^2 emissions and energy consumption. This has produced favorable outcomes. This demonstrates that researchers are currently prioritizing and selecting types of concrete with less environmental pollution to promote sustainability, as evidenced by extensive studies on geopolymers concrete. Fig. 1 shows a significant increase in the number of articles on geopolymers, and interest in geopolymers is noticeably higher than in reactive powder concrete and ready-mix concrete.

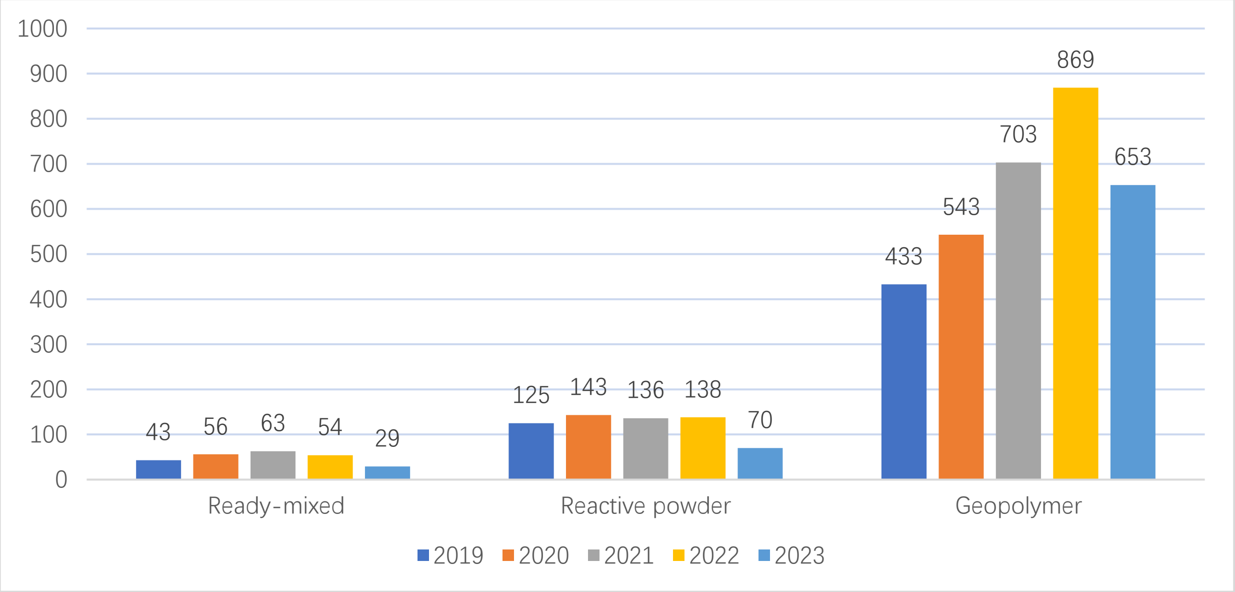

Figure 1. Number of articles published on ready-mix concrete, reactive powder concrete, and geopolymers concrete [8]

2.2. Structure and Reaction Mechanism

2.2.1. Structure.

The structure of geopolymers refers to the Al-O-Si framework composed of Si and Al tetrahedrons connected by oxygen atoms. According to Davidovits' research, the structural formula of geopolymers can be expressed as $M_x[–(SiO_2)_y–AlO_2]_X\cdot\omega H_2O$ [9]. M_x represents alkali metal cations (such as sodium (Na^+), calcium (Ca^{2+}), or potassium (K^+)), x is the degree of polymerization, ω is the total number of water molecules required for chemical bonding, and y is the silicon-aluminum ratio (Si/Al), which can be 1, 2, or 3.

Based on the silicon-aluminum ratio (y), geopolymers can be classified into the following three types: polysialate (PS), polysialate-siloxo (PSS), and polysialate-disiloxo (PSDS) [10]. PS-type geopolymers tend to have a crystalline structure with good thermal insulation properties. PSS-type geopolymers exhibit high strength and the ability to immobilize harmful ions, while PSDS-type geopolymers demonstrate excellent bonding and fire-resistant properties.

2.2.2. Reaction mechanism.

The reaction mechanism of geopolymers is quite complex, leading to various theories among researchers. However, most agree that geopolymerization can be divided into three main stages [11-13].

(1) The dissolution of aluminosilicate materials in an alkaline solution, where the Al-O and Si-O bonds are broken, releasing free silicon ions (Si^{4+}) and aluminum ions (Al^{3+}). Dissolution is the first and most crucial step.

(2) In an alkaline environment, the materials undergo polymerization, forming a gel. Condensation reactions occur, creating an amorphous -Si-O-Al-O- structure. During this phase, water is expelled due to the hydrolysis reaction.

(3) As the reaction progresses, the gel hardens and condenses into a three-dimensional aluminosilicate network, forming a geopolymers with strength.

These three reactions occur simultaneously. The chemical composition of the aluminosilicate, the nature of the alkaline activator (commonly potassium hydroxide (KOH) or sodium hydroxide (NaOH) as the alkaline activator), and the water content determine the reaction rate and the chemical composition of the reaction products. Insufficient water content can slow the reaction rate.

2.3. Applications

Due to the unique structure of the materials constituting geopolymers, they possess advantages such as high strength, heat resistance, corrosion resistance, durability, and low carbon footprint.

(1) Construction Materials

Geopolymers concrete can serve as an alternative to traditional concrete due to its low carbon and environmentally friendly properties. It has already been applied in construction projects in Australia, with promising results [14]. Additionally, geopolymers, due to their high strength, can be used for structural repairs [15]. Ordinary concrete, when exposed to prolonged rain or seawater, may experience compromised stability and safety. However, geopolymers concrete, with its corrosion resistance, is more suitable for marine construction, offering vast potential in offshore applications.

(2) Fire-Resistant and Heat-Resistant Materials

Geopolymers, made by converting industrial waste into fire-resistant, heat-resistant materials, maintain a compressive strength above 30 MPa even after being exposed to 1000°C for 2 hours, exhibiting superior thermal stability and fire resistance [16]. Additionally, geopolymers have found applications in 3D printing materials, insulation, and other related fields.

3. Mechanical Properties of Geopolymers Concrete

Strength and durability are critical performance factors for geopolymers concrete in engineering applications. Factors such as raw materials, activators, and curing conditions influence its strength, while durability is affected by factors such as wear resistance, porosity, and chemical corrosion resistance. Geopolymers offer better strength and durability compared to traditional cement, and their production process is more energy-efficient and environmentally friendly. As a result, geopolymers can be used as an alternative to cement materials in the production of geopolymers concrete. Due to the wide range of raw materials available for geopolymers production, their performance is influenced by various factors. This paper categorizes geopolymers based on their raw materials to study their mechanical properties. Common raw materials for geopolymers concrete include fly ash, metakaolin, and slag.

3.1. Fly Ash-Based Geopolymers Concrete

Fly ash-based geopolymers concrete is made from fly ash and slag, using sodium hydroxide and sodium silicate as activators. By adjusting the mix proportions, concrete with specific properties is produced. This concrete exhibit high compressive strength, good workability, rapid setting, and stable strength characteristics.

The properties of fly ash-derived geopolymers concrete can be adjusted by altering parameters including the water-to-binder ratio, sand content, solution concentration, and mixing ratios. Specifically, when utilizing a water-to-binder ratio of 0.26, a sand content of 0.40, a mass ratio of 0.29 for sodium hydroxide to sodium silicate, and an alkaline solution concentration of 56%, the slag-fly ash-derived geopolymers concrete demonstrates superior characteristics. These include a slump of 110 mm and compressive strengths of 40.4 MPa, 50.3 MPa, and 60.20 MPa after 7, 14, and 28 days of curing, respectively. Additionally, an increase in the water-to-binder ratio enhances workability, whereas compressive strength initially rises but subsequently declines. As curing time extends, compressive strength continues to augment, albeit at a reduced pace [17]. A decrease in the liquid-to-solid ratio from 0.75 results in an increase in compressive strength, peaking at a ratio of 0.49. Maintaining the liquid-to-solid ratio constant, compressive strength progressively elevates as the sodium hydroxide concentration rises from 4.47 mol/L to 6.6 mol/L. Moreover, within a sodium hydroxide concentration range of 6.5 to 7.5 mol/L, compressive strength escalates with an increase in silica content, attaining a maximum at 2.31 mol/L [18]. Investigations into the compressive strength of fly ash-derived geopolymers concrete, taking into account variables such as sodium hydroxide and alkaline slag content, indicate that elevating the alkaline solution concentration and the liquid-to-solid ratio diminishes compressive strength. When the liquid-to-solid ratio is 0.75 and the sodium hydroxide concentration is 8 mol/L, an excessive amount of alkali is present in the system [19]. In conclusion, the mechanical properties of fly ash-derived geopolymers concrete are most favorable when the liquid-to-solid ratio is 0.5 and the sodium hydroxide concentration is 6.6 mol/L.

Moreover, high-temperature curing can significantly enhance the mechanical strength of fly ash-based geopolymers concrete. Compared to standard curing, compressive, flexural, and split tensile strengths increase by more than 88% after high-temperature curing at all curing ages [20].

3.2. Metakaolin-Based Geopolymers Concrete

Metakaolin-based geopolymers concrete is formed through depolymerization and polycondensation, where precursor materials rich in silicon and aluminum react in an alkaline environment, resulting in an inorganic material with a three-dimensional polymer-like structure. This type of geopolymers concrete exhibits early high strength, corrosion resistance, freeze-thaw resistance, and heat resistance.

Studies show that metakaolin-based geopolymers concrete demonstrates excellent performance in terms of uniaxial compressive strength and Young’s modulus. Additionally, the bond strength between metakaolin-based geopolymers concrete and reinforcing steel is higher compared to ordinary concrete, requiring thinner protective layers and shorter bonding lengths, thus improving load transfer efficiency [21].

Other studies have explored the mechanical properties of metakaolin-based geopolymers concrete by varying the concentration of sodium hydroxide solution. The results indicate that increasing the sodium hydroxide concentration enhances both the compressive and flexural strengths, reaching approximately 65 MPa and 50 MPa, respectively, at 35 days [22].

Furthermore, adding slag can improve the mechanical properties of metakaolin-based geopolymers concrete. In studies where slag-metakaolin geopolymers concrete was prepared with a liquid-to-solid ratio of 0.8 and a sodium silicate solution concentration of 25%, the results showed that as the slag content increased, the compressive strength first increased and then decreased, reaching a maximum at 15% slag content [23].

3.3. Slag-Based Geopolymers Concrete

Slag-based geopolymers concrete is a type of geopolymers concrete that uses slag as its primary raw material. It exhibits high early strength, excellent acid resistance, and minimal environmental impact, making it a superior green concrete material. The addition of materials such as slag, silica fume, and kaolin can further enhance its mechanical properties.

Studies have been conducted to examine the mechanical attributes of slag-based geopolymers concrete, utilizing slag as the activating agent. These investigations have concentrated on the nature and concentration of alkaline solutions, the modulus of sodium silicate, and the proportion of sodium silicate to alkaline solution. Upon comparing various concentrations of sodium hydroxide and potassium hydroxide solutions, the findings suggest that potassium hydroxide, combined with sodium silicate as the activator, produces the most favorable outcomes. The optimum conditions are achieved with a sodium silicate modulus of 2.33 and a mass ratio of 0.4 for sodium silicate to alkaline solution. When zeolite powder is substituted for slag, the concrete's workability diminishes, and the highest compressive strength is obtained with a 5% substitution rate [24].

Regarding its fundamental mechanical properties, slag-based geopolymers concrete demonstrates outstanding compressive strength, split tensile strength, flexural strength, and elastic modulus. These characteristics are impacted by several factors, including the liquid-to-solid ratio, the concentration of the alkaline solution, the duration of curing, and the temperature.

3.4. Comparison of Different Types of Geopolymers Concrete

Different raw materials used in geopolymers concrete exhibit varying performances due to differences in the molar concentration of acid or alkaline solutions, binder content, curing temperature, and preparation time.

In summary, the mechanical properties of fly ash-based geopolymers concrete are superior to those of metakaolin-based geopolymers concrete. Slag-based geopolymers concrete outperforms both the fly ash and metakaolin systems, offering better overall performance, higher early strength, and greater acid resistance. Table 1 presents a comparative analysis of the three types of geopolymers concrete. As shown in Table 1, geopolymers concrete has a wide range of raw material sources and excellent performance, demonstrating great development potential.

Table 1. Comparative Analysis of Three Types of Geopolymers Concrete

Name	Characteristics	Material Source	Application Scope
Fly Ash-Based Geopolymers Concrete	High compressive strength, good workability, fast setting and hardening, stable strength characteristics	Fly ash and slag	Construction materials: gypsum products, fly ash concrete blocks Decorative materials: artificial stone, tiles
Metakaolin-Based Geopolymers Concrete	Metakaolin-Based Geopolymers Concrete	Metakaolin	Repair works, heavy metal ion solidification, aerospace
Slag-Based Geopolymers Concrete	Early strength, high acid resistance, excellent compressive strength, tensile splitting strength, and flexural strength	Slag	Construction projects Field of construction materials Commercial concrete production

4. Analysis of Carbon Emissions in Geopolymers Concrete

4.1. Impact on the Environment

The environmental implications of geopolymers concrete are examined through three key indicators: global warming potential (GWP), ozone depletion potential (ODP), and acidification potential (AP).

GWP is a metric used to assess the influence of greenhouse gases (GHGs) on global warming. Research indicates that geopolymers concrete exhibits a GWP that is 26-45% lower compared to traditional concrete. ODP quantifies the extent of harm caused by various substances to the Earth's ozone layer. Notably, the ODP of geopolymers concrete is 1.6-2.7 times higher than that of regular concrete [25]. AP reflects the level of acidification induced by substances or activities on the environment. The environmental footprint of geopolymers concrete is influenced by the production of sodium silicate, which involves heat treatment and kiln processes. Although these processes demand greater energy input, the kiln process for sodium silicate production has a comparatively minimal environmental impact.

Studies reveal that while conventional cement concrete has advantages in terms of ODP, AP, and eutrophication, geopolymers concrete contributes more to sustainable green development with respect to GWP. This highlights the trade-offs and balancing acts required when evaluating the overall environmental performance of different concrete types.

4.2. Comparison of Carbon Emissions Between Geopolymers Concrete and Conventional Concrete

As a novel low-carbon material, geopolymers concrete distinguishes itself by substituting cement as a binder with fly ash and slag. It employs sodium hydroxide and sodium silicate solutions as activators, thereby significantly decreasing greenhouse gas emissions. This reduction is primarily attributed to eliminating the high carbon-emitting phases of traditional cement manufacturing in the production of geopolymers concrete. Additionally, the incorporation of fly ash and slag contributes to lowering carbon emissions associated with raw material extraction and processing. Table 2 presents a comparison of greenhouse gas emissions to produce 1 cubic meter of fly ash-based geopolymers concrete versus conventional concrete.

Table 2. Greenhouse Gas Emissions for Producing 1 cubic meter of Concrete (kg CO_2-e) [26]

Category	Fly Ash-Based Geopolymers Concrete	Conventional Concrete
Raw Materials in the Production Process	Coarse aggregate: 2.368	Coarse aggregate: 2.167
	Fine aggregate: 4.112	Fine aggregate: 3.679
	Fly ash: 0	Cement: 298.00
	Alkali activator: Sodium hydroxide: 11.873	Water: 0.2×0.9=0.18 (CO_2-e per ton of water production = 0.9 kg)
	Sodium silicate: 190.320	/
	Water: 0.050 (for alkali activator)	/
Transportation Process	20.267	16.426
Concrete Mixing	1.050	1.050
High-Temperature Curing	43.240	/
Total (kg CO_2-e)	273.280	321.502

The cement component in traditional concrete is responsible for the lion's share of greenhouse gas emissions, constituting roughly 93% of the total. In contrast, for fly ash-based geopolymers concrete, the primary contributors to greenhouse gas emissions are the production of activators and the high-temperature curing process, which together represent approximately 90% of the overall emissions. While fly ash-based geopolymers concrete exhibits increased carbon emissions during the preparation of alkali activators and high-temperature curing compared to conventional concrete, it still boasts a reduction of 48.222 kg per cubic meter in greenhouse gas emissions, equating to a 15% decrease. Consequently, geopolymers concrete presents an effective means of reducing carbon emissions and serves as a viable alternative to traditional concrete.

5. Conclusion

This paper mainly studies the mechanical properties and carbon emissions of geopolymers concrete, leading to the following conclusions:

(1) Geopolymers concrete showcases remarkable mechanical robustness and enduring qualities, attributed to its distinctive three-dimensional network framework resulting from the polymerization of aluminosilicate substances within an alkaline milieu. The variety of constituents, including fly ash, metakaolin, and slag, adds to its diverse performance traits. Research indicates that geopolymers concrete possesses elevated compressive strength, commendable corrosion resistance, high-temperature tolerance, and rapid strength development, with slag-based geopolymers concrete exhibiting exceptional initial strength and acid resilience.

(2) In contrast to traditional cement-based concrete, geopolymers concrete markedly diminishes carbon emissions since it does not depend on cement production, which is a significant emitter of carbon. Even though the utilization of alkali activators and high-temperature curing processes contributes to a minor increase in carbon emissions, the overall manufacturing process of geopolymers concrete cuts greenhouse gas emissions by roughly 15% when compared to conventional concrete. This underscores geopolymers concrete as a sustainable, environmentally beneficial material.

(3) This demonstrates that geopolymers concrete is a sustainable material with environmental advantages. However, its widespread application globally still faces certain challenges, including high activator costs, complex production processes, and insufficient standardization. Future research should further explore its economic feasibility, material ratio optimization, and production process improvements to promote large-scale application of geopolymers concrete.

In conclusion, geopolymers concrete is a green building material with great development potential. Its research and application will play a key role in promoting sustainable development in the construction industry, especially in the context of addressing global climate change and reducing carbon emissions.

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