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Review

Geopolymers as Sustainable Materials: A Short Review

Shova R Bhattarai [1*], Mubarak Adesina [1], Ali Akbari [2]

[1] *Department of Civil and Environmental Engineering, Lamar University, Beaumont, TX, USA*
[2] *RWTH Aachen University, Aachen, Nort Rhine-Westphalia, Germany*

Keywords

Geopolymers, Sustainable construction, Durability performance, Carbon footprint reduction, Economic feasibility.

Abstract

Geopolymers are rising as a preferred green alternative to Portland cement due to their superior mechanical and chemical properties, durability factor, and reduced carbon footprint. This review combines the latest developments in geopolymer research, zeroing in on optimizing raw materials, choosing activators, assessing durability, and keeping costs in check. Mechanochemical activation plays a crucial role in boosting the microstructural integrity of fly ash and dredged sediments, enabling compressive strengths over 80 MPa. Interestingly, new alternative activators, like sodium silicate from coal bottom ash, can cut costs by up to 30% without sacrificing performance compared to conventional sodium silicate. Durability tests reveal that geopolymers have better resistance to sulfate and acid than regular cement. However, the effects of carbonation vary depending on exposure conditions and the composition of the precursor materials. Economic studies suggest that producing geopolymers could lower CO_2 emissions by 25-50% and reduce costs by up to 30%, influenced by the availability of raw materials and processing techniques. However, there are still significant gaps in our knowledge. More validation of geopolymers' long-term performance under different environmental conditions through field trials is needed. Moreover, the inconsistency in industrial by-products makes it tricky to standardize mix designs for consistent mechanical properties. To ensure they endure over time, more extensive research is essential to understand how carbonation affects geopolymer stability in real-world settings. Upcoming studies should focus on refining activator compositions, improving mix ratios, and incorporating reinforcement strategies to boost mechanical strength and durability. Tackling these issues is crucial for the broader adoption of geopolymer technology in sustainable construction.

1. Introduction

The global construction industry contributes significantly to CO_2 emissions, primarily due to the widespread use of Portland cement, which accounts for approximately 7-8% of total emissions worldwide [1,2]. Geopolymer materials, synthesized from industrial by-products, offer a promising alternative with lower carbon emissions and enhanced mechanical performance. The main components of geopolymers are fly ash, slag, bottom ash, dredged sediments, and silica-rich waste materials. These materials are activated using alkaline solutions such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) [3–5]. Geopolymers provide an alternative, reducing carbon footprint by up to 80% while maintaining high mechanical strength and durability [1,6]. However, optimizing geopolymer formulations remains challenging, particularly regarding raw material variability, activator efficiency, and long-term durability.

This review investigates several essential factors that influence how well geopolymers perform, including:

* Corresponding Author: Shova R Bhattarai
E-mail address: shovarambhattarai326@gmail.com, ORCID: https://orcid.org/0009-0001-3050-3165

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i). A closer look at how materials like fly ash, bottom ash, dredged sediments, slag, and commercial sodium silicate with other activators impact compressive strength and overall durability.

ii) A comparison of the costs of geopolymers and their potential for reducing CO_2 emissions against traditional cement materials.

This investigation covers methodology, material optimization, mechanical and durability performance, economic feasibility, and sustainability. It also includes suggestions for future research, particularly around large-scale applications and optimizing activators.

2. Methodology

A brief review focused on recent research examining geopolymers' mechanical properties, durability, and economic viability. Studies were selected based on their relevance to optimizing raw materials, activators' efficiency, carbonation effects, and sustainability assessments. Data from published experimental studies were gathered and analyzed to pinpoint trends and gaps within geopolymer research.

3. Material Optimization

3.1 Effect of Raw Materials on Mechanical Properties

Mechanochemical activation of dredged sediments and bottom ash has been shown to enhance reactivity, leading to compressive strengths exceeding 80 MPa [5]. Fly ash-slag blends further improve early strength development and sulfate resistance [7]. The properties of different geopolymer formulations depend largely on precursor materials, which influence setting time, density, and overall performance [8,9]. Table 1 summarizes the effects of different precursor materials on geopolymer properties.

Table 1. Different precursor materials' role in geopolymer properties [3,5,10].

Material	Strength	Durability	Remarks
Fly Ash	Moderate to high (40–80 MPa)	Improved sulfate resistance	Requires alkali activation
Ground Granulated Blast Slag	High (60–100 MPa)	Enhanced early strength	Reduces setting time
Bottom Ash	Moderate (30–60 MPa)	Improved thermal resistance	Enhances microstructure
Dredged Sediments	Low (up to 40 MPa)	Variable requires modification	It can be used as a partial replacement

3.2. Influence of Alternative Activators

Coal bottom ash-derived sodium silicate has demonstrated cost reductions of up to 30% while maintaining comparable compressive strength to commercial activators [8,11,12]. This offers a viable alternative to costly commercial activators while enhancing sustainability. Other alternative activators include rice husk ash-based solutions, which improve setting time and strength but require further refinement for large-scale applications [13]. Additionally, alkaline activators derived from agricultural waste, such as palm oil fuel ash, have been explored as a sustainable alternative due to their high silica content, though their reactivity varies depending on processing conditions [3,14]. The combination of multiple alternative activators, such as a blend of sodium carbonate and potassium silicate, has also shown promising results in enhancing strength development while reducing material costs [7]. Future studies should focus on optimizing these alternative activators for large-scale applications by addressing inconsistencies in chemical compositions and improving reaction kinetics.

4. Mechanical and Durability Performance

4.1. Strength and Shrinkage Behavior

The strength and shrinkage behavior of geopolymer materials are crucial factors in determining their suitability for structural applications. The compressive strength of geopolymer concrete depends on precursor materials, activator concentrations, curing conditions, and mix proportions. Studies have shown that geopolymer concrete with high slag content can achieve compressive strengths exceeding 100 MPa, making it suitable for high-strength applications [7].

Additionally, fly ash-based geopolymers, when cured under elevated temperatures, have been shown to develop higher early strengths compared to ambient-cured samples, reaching up to 80 MPa within 7 days [15,16]. Blended systems incorporating metakaolin have demonstrated a reduction in shrinkage of up to 50% compared to fly ash-only systems, contributing to improved dimensional stability [3]. A variety range of strength has been reported from 0-56 MPa In the low loading dredge sediment geopolymer systems as well as same range for the high loading dredge sediment geopolymer systems [5].

Table 2 summarizes the strength and shrinkage behavior of different geopolymer compositions.

Table 2. Strength and shrinkage behavior of different geopolymer compositions [5,7,10,17,18]

Composition	Compressive Strength (MPa)	Shrinkage Behavior	Key Observations
Fly Ash-Based Geopolymer	40–80 MPa	Low to Moderate	Requires high alkali activation for strength development
Slag-Based Geopolymer	60–100 MPa	Low	Fast setting and high early strength
Bottom Ash-Based Geopolymer	30–60 MPa	Moderate	Improved durability but requires optimization
Fly Ash + Slag + Metakaolin	80-120 MPa	Very Low	Best performance in strength and shrinkage reduction

Future research should focus on refining mix proportions, optimizing activator compositions, and incorporating innovative reinforcement strategies such as fiber additives to enhance strength while minimizing shrinkage effects. Additionally, long-term studies on creep and shrinkage under different environmental conditions are needed to validate the stability of geopolymer materials in real-world applications [13].

4.2. Durability and Carbonation

Durability is a key consideration for geopolymer applications in structural construction. Factors such as sulfate resistance, freeze-thaw durability, and carbonation effects influence the long-term performance of geopolymer materials. Studies have shown that geopolymers exhibit superior sulfate resistance compared to Portland cement due to their lower calcium content, which reduces the risk of ettringite formation [7,19–21].

Carbonation, however, remains a critical factor in geopolymer performance [22]. Accelerated carbonation leads to the formation of sodium bicarbonate, which can alter the pH and affect long-term stability. Natural carbonation produces natron, which does not significantly impact mechanical properties but may affect microstructural stability [23].

Future studies should optimize mix proportions to enhance durability while minimizing carbonation effects. Field exposure studies are also necessary to validate laboratory findings and ensure real-world performance stability.

A summary of the durability and carbonation properties of different geopolymer formulations is presented in Table 3.

Table 3. Durability and carbonation properties of different geopolymer formulations [5,7,10,17,18]

Composition	Sulfate Resistance	Freeze-Thaw Durability	Carbonation Effect	Key Observations
Fly Ash-Based Geopolymer	High	Moderate	Moderate	Requires high curing temperature for durability
Slag-Based Geopolymer	Very High	High	Low	Best for aggressive environments
Bottom Ash-Based Geopolymer	Moderate	Low	High	Requires mix optimization for stability
Fly Ash + Slag + Metakaolin	Very High	Very High	Low	Best combination for durability and carbonation resistance

5. Economic Feasibility and Sustainability

Economic feasibility plays a critical role in the adoption of geopolymer technology. Geopolymers' primary advantages are their ability to utilize industrial waste products such as fly ash and slag, which reduces dependency on virgin materials and lowers costs. Studies have shown that the production cost of geopolymer concrete can be reduced by up to 30% compared to traditional Portland cement-based concrete due to the use of alternative binders [1].

In addition to cost savings, the environmental benefits of geopolymers further enhance their sustainability. The carbon footprint of geopolymer concrete is significantly lower than that of Portland cement due to the elimination of the calcination process required for clinker production. This results in a reduction of CO_2 emissions by approximately 25–50%, making geopolymer materials a viable alternative for reducing greenhouse gas emissions [24]. Furthermore, the ability of geopolymers to incorporate locally available materials can reduce transportation costs and further improve their economic viability [7]. Table 4 presents key economic and sustainability factors of geopolymer concrete.

Despite these advantages, some challenges remain in the widespread adoption of geopolymers. The availability and consistency of raw materials such as fly ash and slag can vary, impacting production efficiency. Additionally, while geopolymers exhibit superior durability in sulfate and acid environments, their long-term performance under varying climatic conditions requires further validation through field studies [11].

Future studies can focus on enhancing mix design optimization, creating standardized testing procedures, and raising awareness about geopolymer's economic and environmental advantages. Additionally, government incentives and supportive policies can be essential in speeding up the adoption of geopolymer technology within the construction sector.

Table 4. Economic and sustainability factors of geopolymer concrete [1,2,17,18,25–27]

Factor	Geopolymer Concrete	Portland Cement Concrete	Remarks
Production Cost	20-30% lower	Higher due to clinker production	Cost savings depend on material availability
CO_2 Emissions	25-50% lower	High emissions from calcination	Significant environmental benefits
Raw Material Usage	Industrial by-products	Virgin materials	Utilizes waste, reducing landfill burden
Energy Consumption	Lower	High due to cement production	Less energy-intensive manufacturing

Durability	High sulfate and acid resistance	Moderate sulfate resistance	Longer service life for geopolymer concrete

6. Conclusion

Geopolymers hold significant promise as sustainable alternatives to Portland cement, offering a pathway to reduce the environmental footprint of the construction industry. Their impressive compressive strengths, reaching 120 MPa in optimized formulations [28,29], coupled with a potential for a reduction in CO_2 emissions [30] compared to conventional cement production, present a compelling case for their adoption. The economic advantages of utilizing industrial by-products like fly ash, slag, and bottom ash, leading to potential cost savings, further enhance their appeal [31]. Furthermore, geopolymers exhibit superior durability compared to traditional cement, particularly in aggressive environments with high sulfate and acid concentrations, making them attractive for long-term applications [32–34].

Despite these advantages, several critical research gaps remain. A comprehensive understanding of long-term performance under diverse climatic conditions is crucial. The inherent variability in raw material sources necessitates the development of standardized mix designs that ensure consistent and reliable performance. A more detailed investigation of carbonation effects under real-world exposure conditions is also needed to guarantee long-term stability. Similarly, extensive field trials are essential to validate laboratory findings and assess the performance of geopolymers in large-scale industrial settings.

Future research should prioritize optimizing mix proportions and activator blends and exploring effective reinforcement strategies to enhance durability and strength. Collaborative efforts between academia and industry are vital for accelerating the adoption of geopolymers and establishing standardized practices for broader implementation in infrastructure projects. Addressing these challenges will pave the way for geopolymers to become a mainstream construction material, contributing significantly to global sustainability goals.

Declaration of Interest

There is no conflict of interest in connection to the work submitted.

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