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The potential of fly ash-based geopolymers as an environmentally friendly construction material solution: a review

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Abstract. The use of environmentally friendly construction materials has been increasing in response to the demand for sustainable development. Fly ash-based geopolymers have emerged as an innovative and sustainable solution in the construction industry. This article discusses the potential use of fly ash-based geopolymers, covering their characteristics, synthesis process, advantages, challenges, and future development prospects. This research adopts a literature review approach, referencing various international and national journals. The study findings reveal that fly ash geopolymers possess high mechanical strength, corrosion resistance, and significantly lower carbon emissions compared to conventional concrete. This potential provides significant opportunities in supporting more environmentally friendly infrastructure development.

Keywords: geopolymer, fly ash, construction materials, environmentally friendly, sustainable development

INTRODUCTION

Sustainable infrastructure development has become a key priority in addressing global challenges related to climate change and environmental preservation. The construction sector plays a significant role in carbon emissions, particularly through the production of Portland cement, which is one of the largest contributors to CO_2 emissions. This has driven the search for alternative construction materials that are not only environmentally friendly but also have a lower carbon footprint. One such emerging innovation is fly ash-based geopolymer, a material derived from industrial waste in the form of fly ash, which is produced by coal-fired power plants (PLTU). This provides an opportunity to transform industrial waste into a high-value material [1–6].

A geopolymer is defined as an inorganic material formed through an alkali polymerization process involving compounds rich in silica (SiO_2) and alumina (Al_2O_3). Fly ash, which contains these compounds in large quantities, becomes an ideal raw material for geopolymer production. The synthesis process of fly ash-based geopolymer involves a chemical reaction between fly ash and an alkali solution, such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), resulting in a three-dimensional structure with superior mechanical properties, including high strength, corrosion resistance, and exceptional thermal stability [7–10].

The main advantage of fly ash-based geopolymer lies in its ability to reduce carbon emissions by up to 80% compared to Portland cement-based concrete [11]. Moreover, the use of fly ash, which was previously considered hazardous waste, helps reduce environmental pollution while supporting the principles of the circular economy by transforming waste into a high-value product [12]. However, the industrial-scale application of fly ash-based geopolymer faces challenges, such as the availability of fly ash, which depends on the location of power plants, high production costs due to the need for alkaline materials, and limited regulations and technical standards in various countries [13–15].

Therefore, this study aims to explore the potential of fly ash-based geopolymer as an alternative, environmentally friendly construction material. The focus of this review is on the material's characteristics, synthesis process, advantages over conventional materials, and the challenges and prospects for its future development. Using a literature review approach, this article comprehensively examines the potential of fly ash-based geopolymer in supporting sustainable and environmentally friendly infrastructure development.

METHODOLOGY

This study was conducted using a literature review method, drawing from various international and national journal sources. Data were obtained from the Google Scholar database. The article selection process focused on studies that discuss the synthesis, characteristics, and applications of fly ash-based geopolymers. All articles were identified and analyzed to identify relevant findings.

RESULTS AND DISCUSSION

Mechanical strength

Fly ash-based geopolymer materials are gaining recognition as sustainable alternatives to conventional construction materials due to their significant mechanical strength and environmental benefits. The compressive strength of these geopolymers is influenced by a combination of factors, including raw material characteristics, alkali content, synthesis conditions, and curing methods. Optimizing these parameters has demonstrated substantial improvements, positioning fly ash-based geopolymers as viable solutions in modern construction practices. The characteristics of raw materials, such as the amorphous phase content (APC) and particle size distribution (PSD), critically affect the compressive strength of fly ash-based geopolymers. Adjusting these parameters, particularly through the incorporation of ground granulated blast furnace slag (GGBS), has shown to enhance the microstructure and mechanical properties of the final product [16]. Studies indicate that the addition of GGBS not only improves compressive strength but also significantly reduces the setting time, particularly when activated with sodium hydroxide solutions of varying molarities [17,18].

The alkali content, specifically the sodium oxide (Na_2O) content and the alkali modulus, plays a pivotal role in determining the mechanical properties of geopolymers. A higher Na_2O content paired with a lower alkali modulus has been found to enhance both the compressive strength and the fluidity of the geopolymer mixtures [19]. Similarly, curing methods are instrumental in achieving optimal results. Among various curing techniques, ambient curing has demonstrated superior compressive strength compared to methods such as hot air oven curing and humidity chamber curing [18]. Fly ash-based geopolymer concrete consistently outperforms conventional concrete in terms of compressive strength, splitting tensile strength, and modulus of elasticity. These advantages not only reinforce its mechanical superiority but also highlight its potential as a sustainable construction material with reduced carbon emissions [20].

Fly ash-based geopolymers have proven to enhance mechanical strength significantly, making them a sustainable alternative to traditional materials. Geopolymers utilizing municipal solid waste incineration fly ash (MSWI FA) demonstrated compressive strengths exceeding 60 MPa with 50% MSWI FA content [21]. Similarly, Class C fly ash-based geopolymer mortar achieved a maximum compressive strength of 70.80 MPa at a 60:40 fly ash-to-activator ratio, while the same material reached a flexural strength of 12.19 MPa at a 70:30 ratio [22]. Reinforcement with polyvinyl alcohol

(PVA) fibers increased flexural strength to 13.16 MPa, marking a 150.95% improvement compared to the control group [23]. Additionally, the splitting tensile strength of Class C fly ash mortar was recorded at 26.33 MPa [22]. The combination of fly ash with slag further enhances compressive and flexural properties due to synergistic effects between the materials [23]. However, challenges related to long-term durability and environmental impacts under extreme conditions remain [21]. Addressing these issues is crucial for the broader adoption of fly ash-based geopolymers in sustainable construction.

Despite these promising attributes, challenges persist in refining the geo-polymerization process, particularly at lower temperatures, to broaden the applicability of fly ash-based geopolymers in diverse construction scenarios. Further research is essential to address these limitations, optimize raw material usage, and enhance the scalability of production processes for widespread adoption.

Environmental durability

Fly ash-based geopolymers exhibit exceptional environmental durability, particularly in resisting corrosion, water penetration, and freeze-thaw cycles. These qualities make them a sustainable alternative to conventional concrete. Their unique composition, enriched with silica and alumina, forms a robust binding matrix that not only enhances durability but also reduces the need for frequent maintenance.

Fly ash-based geopolymers demonstrate superior resistance to corrosion compared to ordinary Portland cement (OPC) concrete, especially in aggressive environments such as marine conditions. A study found that fiber-reinforced geopolymer structural concrete exhibited a 24% reduction in crack severity and a 109% increase in residual flexural load capacity in simulated marine environments [24]. This improved resistance is attributed to the alkaline environment generated during geopolymer synthesis, which protects embedded steel reinforcements from corrosion [25]. Geopolymer concrete has significantly lower water absorption rates compared to OPC concrete, with moderate permeability depths ranging from 5 to 20 mm [26]. This reduced permeability minimizes water ingress, thereby preventing chemical degradation and structural damage. Additionally, the dense microstructure of fly ash-based geopolymers enhances their resistance to freeze-thaw cycles, a critical factor for maintaining structural integrity in regions with fluctuating temperatures [27].

The use of fly ash in geopolymer production significantly reduces the carbon footprint associated with traditional cement-based materials. Studies report a 29.6–35.4% reduction in the global warming potential of fly ash-based geopolymer mortar compared to cement mortar [28]. Furthermore, the enhanced durability and extended service life of geopolymer materials translate to lower maintenance costs, further reinforcing their sustainability [25]. Despite these advantages, fly ash-based geopolymers face challenges that could affect their performance in real-world applications. Variability in fly ash quality and the need for precise control over the activation process can lead to inconsistencies in material properties. Addressing these challenges requires standardized practices and advanced quality control measures during production.

Environmental impact

Fly ash-based geopolymers provide a sustainable alternative to traditional Portland cement, offering significant reductions in carbon emissions within the construction industry [11,29,30]. Unlike cement production, which requires high-energy processes at temperatures ranging from 1400–1600 °C, geopolymer synthesis operates at much lower temperatures of 60–100°C, resulting in reduced energy consumption and greenhouse gas emissions. Research indicates that geopolymer concrete can reduce carbon emissions by up to 68% compared to conventional concrete while maintaining or exceeding comparable mechanical properties [31,32]. Furthermore, fly ash-based geopolymers have a lower carbon footprint, reducing emissions by approximately 30% relative to OPC concrete [31]. These materials also exhibit remarkable energy efficiency due to their low production temperatures [33].

In terms of mechanical properties, geopolymers demonstrate strengths comparable to or even exceeding Portland cement. Certain formulations achieve up to 88% higher compressive strength at early ages [32]. Additionally, they exhibit enhanced durability in aggressive environments, such as resistance to harsh chemical exposures, freeze-thaw cycles, and other environmental stressors, making them ideal for various applications [34]. Despite these advantages, challenges remain in the widespread adoption of fly ash-based geopolymers. These include variability in the quality of fly ash, the scalability of production processes, and the need for further research into their long-term performance and sustainability in diverse environmental conditions. Addressing these issues will be crucial to maximizing the potential of fly ash-based geopolymers as a sustainable and durable construction material.

Fly ash-based geopolymers provide a viable alternative to traditional Portland cement by offering substantial reductions in carbon emissions due to their lower production temperatures and the use of industrial by-products. Portland cement production is a significant source of global CO_2 emissions, contributing approximately 8% of the total due to the high temperatures required for its synthesis. In contrast, geopolymers are produced at much lower temperatures, leading to reduced energy consumption and associated emissions. The incorporation of fly ash, a by-product of coal combustion, not only reduces waste but also supports environmental sustainability by mitigating emissions and minimizing the environmental footprint compared to traditional cement [31,35]. Geopolymers are capable of reducing carbon emissions by up to 30% compared to OPC, demonstrating their potential as a green construction material. Furthermore, the utilization of industrial by-products like fly ash aligns with the principles of the circular economy, ensuring more sustainable use of resources [36–38].

From a technical standpoint, fly ash-based geopolymers possess excellent mechanical properties that enhance the strength and durability of concrete structures [36]. However, the adoption of this material faces economic challenges, as its cost-effectiveness is critical for broader industry acceptance. Research has shown that optimizing mix proportions and activator dosages can result in significant cost savings while reducing emissions [39]. Despite these benefits, challenges related to the scalability and economic viability of geopolymer production remain. Continued research is essential to improve formulations, lower costs, and ensure consistent performance, thereby paving the way for geopolymers to contribute significantly to the reduction of carbon emissions in the construction industry.

Advantage and challenges

Fly ash-based geopolymers offer significant advantages in the context of environmental sustainability. One of their key benefits is the ability to reduce carbon emissions during cement production. Compared to conventional cement, which generates high carbon dioxide emissions due to the high-temperature limestone combustion process, geopolymers do not require such a process. The production of geopolymers takes place at much lower temperatures, significantly reducing the carbon footprint. This makes them an environmentally friendly alternative that aligns with global efforts to mitigate climate change. Moreover, fly ash-based geopolymers utilize industrial waste, specifically fly ash, which is a by-product of coal combustion in power plants. This waste, when not properly managed, often leads to environmental pollution. By converting fly ash into construction material, geopolymers not only reduce waste but also add value to a material previously considered industrial waste, thus supporting the circular economy.

Geopolymers also exhibit comparable or even superior strength and durability to conventional concrete. They show higher resistance to aggressive environments such as acidic, sulphate, and high-temperature conditions. This makes them suitable for use in extreme environments, such as structures exposed to seawater or those requiring fire and heat resistance. The compressive strength of geopolymers is also comparable to regular concrete, making them a reliable material choice for infrastructure projects.

Despite their many advantages, several challenges remain in the implementation of fly ash-based geopolymers. One primary challenge is the need for strict temperature and humidity control during production. The chemical activation process involving fly ash and alkaline solutions requires precise temperature settings and curing time to ensure high-quality material production. Without proper control, the quality of the geopolymer can deteriorate, reducing its strength and durability. Another challenge is the availability of high-quality fly ash. While fly ash is produced in large quantities, not all fly ash has the appropriate chemical composition for producing quality geopolymers. High carbon content or excessive heavy metals can interfere with the formation of geopolymer bonds, affecting the final material’s quality. Additionally, regions reducing their reliance on coal-fired power plants may face limited supplies of suitable fly ash, making the sustainability of this raw material a critical issue.

CONCLUSION

Fly ash-based geopolymers have significant potential to become an environmentally friendly construction material. Their advantages in reducing carbon emissions, utilizing waste, and offering excellent strength and durability make them an attractive alternative to conventional concrete. However, challenges related to production control and raw material availability must be addressed to promote wider adoption. With further innovations in production technology and fly ash supply management, fly ash-based geopolymers can play a crucial role in creating greener and more sustainable infrastructure.

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