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ORIGINAL ARTICLE

Optimizing Geopolymer Concrete: A Review of Silica Fume as an Alternative Alkaline Activator

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ABSTRACT - In recent years, geopolymer concrete has gained attention as a sustainable alternative to traditional concrete due to its reduced greenhouse gas emissions and effective use of industrial by-products. This study reviews the benefits of geopolymer concrete, focusing on the use of silica fume as an alternative to sodium silicate. Silica fume, a by-product of silicon alloy production, offers significant advantages in terms of performance and environmental impact. Compared to sodium silicate, silica fume enhances compressive strength, reduces porosity, and improves the overall durability of geopolymer concrete. Additionally, it supports sustainability by lowering reliance on energy-intensive production processes and reducing carbon emissions. The study highlights that silica fume's fine particles fill voids in the concrete matrix, leading to a denser structure and fewer cracks. Despite these advantages, further research is needed to optimize silica fume's application in geopolymer concrete and to address any associated performance challenges. Overall, incorporating silica fume in geopolymer concrete formulations presents a promising approach to advancing both material performance and environmental sustainability in construction.

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INTRODUCTION

In recent years, there has been a growing trend towards the use of geopolymer concrete as an alternative to traditional concrete in construction projects. Geopolymer concrete offers several advantages over its conventional counterpart. Firstly, it exhibits significantly lower greenhouse gas emissions during production due to its reduced reliance on Portland cement, a major source of CO_2 emissions. Moreover, the use of industrial by-products such as fly ash or slag in geopolymer concrete contributes to waste reduction and promotes sustainability [1].

Geopolymer concrete offers several advantages over conventional concrete. It boasts better early strength development, improved resistance to chemical attacks, and efficient thermal insulation properties [2]. Moreover, it requires shorter curing time and experiences less shrinkage and creep, ensuring long-term structural integrity. Researchers and engineers are actively exploring fly ash-based geopolymer concrete to enhance its performance and acceptance in the construction sector. By understanding its distinct behaviour, they aim to revolutionize the construction industry and promote a greener, more sustainable built environment [3].

Materials rich in silicon and aluminum, like fly ash or slag, are categorized as aluminosilicates in geopolymer concrete. These substances replace traditional cement and undergo geopolymerization when mixed with an alkaline solution. This chemical reaction forms a robust and durable binder that holds the concrete together. Geopolymer concrete offers environmental benefits by reducing carbon emissions and utilizing industrial waste, contrasting with conventional concrete [4].

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Past research has commonly employed a method involving the combination of fly ash with sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) as alkaline activators to produce geopolymer concrete. This process typically begins with the mixing of fly ash with an alkaline solution containing sodium hydroxide and sodium silicate environment [3]. The alkaline activators initiate a chemical reaction between the silica and alumina present in the fly ash, resulting in the formation of a geopolymer gel. This gel acts as the binder, binding together the aggregate particles to form a solid concrete matrix. The proportions of fly ash, sodium hydroxide, and sodium silicate, as well as the curing conditions, are carefully controlled to achieve the desired properties of the geopolymer concrete. This method offers an environmentally friendly alternative to traditional concrete production by utilizing industrial by-products such as fly ash and reducing the reliance on Portland cement, thereby lowering greenhouse gas emissions associated with concrete production [5]. However, challenges such as controlling the setting time, achieving desired strength properties, and ensuring consistent performance across different mixtures still require further research and development efforts [6].

The objective of this paper is to review and compare studies focusing on alkaline activator alternatives for geopolymer concrete. Various studies have experimented with aluminosilicates such as fly ash, metakaolin, slag, and silica fume. However, few have conducted research on silica fume as an activator. This study aims to identify the advantages of using silica fume as a substitute for sodium silicate in alkaline activators. Specifically, this paper explores the impact of silica fume on the strength of geopolymer concrete, examining how its inclusion as an activator can enhance the mechanical properties and overall performance of the material.

SODIUM SILICATE ALTERNATIVE

Past studies have explored alternative approaches to reduce or eliminate the use of energy-intensive sodium silicate in the production process of geopolymer. Research focused on substituting sodium silicate with rice husk ash (RHA) in metakaolin geopolymer cement found that RHA-based sodium silicate, cured at room temperature, exhibited characteristics comparable to commercial sodium silicate [7]. Satisfactory results were also achieved in metakaolin-based geopolymer production using alternative alkaline activators made from waste glass and RHA [8]. Additionally, sodium silicate derived from sugar cane straw ash and sodium hydroxide produced results similar to RHA-based geopolymer when Ground Granulated Blast-furnace Slag (GGBS) was used as a substitute. These studies underscore the potential viability of alternative approaches to reduce the dependency on sodium silicate in geopolymer production [9]. Further research and development could optimize these processes for broader adoption in the construction industry.

One reason for seeking alternatives to sodium silicate in geopolymer concrete production is its energy-intensive and costly manufacturing process. Commercial sodium silicate is typically produced by heating a mixture of sodium carbonate (Na_2CO_3) and quartz (SiO_2) at very high temperatures, often between 1400 and 1500°C. This process demands significant energy inputs and results in substantial carbon emissions, which contradict sustainability goals for alternative materials like geopolymer concrete [10]. The drive towards alternatives reflects the construction industry's need for more sustainable, cost-effective, and environmentally friendly materials. Reducing reliance on energy-intensive sodium silicate through the use of waste materials and byproducts can significantly enhance the sustainability of geopolymer concrete. Continued research and innovation in this area are crucial for developing viable alternatives that meet commercial sodium silicate's performance standards while aligning with environmental and economic goals.

Silica fume presents a promising substitute for sodium silicate in geopolymer concrete production due to its pozzolanic properties and availability as an industrial by-product. Silica fume is obtained from the production of silicon alloys and ferrosilicon, thus minimizing the need for additional energy-intensive manufacturing processes [11]. Its ultrafine particle size and high surface area make it an effective supplementary cementitious material in geopolymer concrete formulations, offering comparable or superior performance to sodium silicate while reducing environmental impact [12]. This shift towards silica fume underscores the construction industry's commitment to sustainable practices and reducing carbon footprints in concrete production. Silica fume's attributes make it an attractive option for advancing sustainable construction practices, aligning with goals to lower carbon footprints and promote eco-friendly materials.

Research has demonstrated that utilizing industrial waste fly ash to produce geopolymer at ambient temperatures can reduce greenhouse gas emissions by 26–80% compared to Portland cement [13]. Studies indicated that geopolymer concrete emits 9% less CO_2 than Portland cement-based concrete. Disparities between studies arise from variations in raw material proximity, availability, composition, energy/fuel types, concrete mix compositions, and manufacturing processes for alkaline activators [14]. Despite sodium silicate's widespread use in alkaline activation, its application significantly increases embodied energy and CO_2 emissions in geopolymer manufacturing processes. The energy-intensive and costly production of sodium silicate can hinder the sustainability of geopolymer binder production compared to Portland cement [15]. Studies underscore geopolymer concrete's substantial environmental benefits over Portland cement, particularly in reducing greenhouse gas emissions. However, sodium silicate usage in geopolymer production poses challenges related to energy consumption and CO_2 emissions. Addressing these challenges through alternative activators and optimized production processes is critical for enhancing geopolymer concrete's sustainability and maximizing its environmental benefits. Ongoing research and innovation are crucial as the construction industry seeks greener alternatives.

One of silica fume's primary advantages in geopolymer concrete is its capacity to enhance mechanical properties and durability. Silica fume particles are extremely small, offering high surface area and reactivity, which improves concrete matrix packing and densification [16]. This leads to enhanced strength, reduced permeability, and improved resistance to chemical attacks and environmental degradation. Moreover, silica fume promotes sustainability by utilizing an industrial by-product and reducing the demand for Portland cement, a major source of greenhouse gas emissions [17]. Integrating silica fume into geopolymer concrete formulations allows construction projects to achieve superior environmental performance alongside excellent mechanical properties and durability. The use of silica fume represents a significant step towards advancing the capabilities and ecological benefits of geopolymer concrete in construction projects.

Overall, silica fume presents a promising alternative to sodium silicate in geopolymer concrete production, offering technical and environmental benefits that support sustainable construction practices. Despite its wide-ranging applications as an amorphous Supplementary Cementing Material, there remains a need for extensive research on utilizing silica fume as an activator raw material in geopolymer technology [18; 19].

MECHANICAL PROPERTIES

According to recent research, when silica fume is used as an activator in geopolymer concrete, its fine particles effectively fill the pores in the cementitious system, resulting in a smooth and flat surface. Experimental results show that incorporating 10% silica fume (specimen C) in the mixture leads to a compressive strength exceeding 40 MPa at 28 days, whereas specimens using sodium silicate as the activator (specimen A) achieve only 34 MPa. Researchers also observed that geopolymer concrete activated with silica fume exhibits fewer internal pores and cracks compared to those activated with sodium silicate, particularly when compressive strength exceeds 39.1 MPa [20]. This supports the notion that while both silica fume and sodium silicate are effective activators for geopolymer concrete, silica fume offers superior benefits in terms of strength and microstructural integrity. Silica fume's ability to enhance particle packing and reduce pore size creates a denser and smoother surface, contributing to increased durability. In contrast, sodium silicate aids in crack repair due to its viscosity but does not achieve the same level of strength enhancement as silica fume.

In another study, researchers explored substituting sodium hydroxide in the alkaline activator with calcium carbide residue (CCR) to form a solid alkaline activator mixed with silica fume for geopolymer binders using fly ash or slag as aluminosilicates. The study investigated the impact of varying silica fume content alongside a fixed 12 wt% CCR content on the polymerization reaction in geopolymers. Results indicated that higher silica fume content corresponded to increased compressive strength. Notably, a mixture containing 6 wt% silica fume achieved a high compressive strength of 43 MPa at 56 days, demonstrating accelerated strength development in the calcium carbide residue-fly ash/slag (FAS) geopolymer binder. This improvement is attributed to the abundant non-crystalline silica in silica fume, which reacts with Ca(OH)2 in calcium carbide residue, leading to the formation of more C-(A)-S-H gel and a denser microstructure [22]. The combination of CCR and silica fume proves effective in producing robust and durable geopolymer binders, utilizing waste materials while enhancing binder performance compared to traditional activators like sodium hydroxide.

A comparative study evaluated the performance of silica fume and sodium silicate in geopolymer binders with metakaolin (MK) and ground granulated blast furnace slag (GGBS) as aluminosilicates. Results indicated that GGBS-based pastes exhibited higher strength compared to MK-based ones due to differences in their binding systems. The sodium silicate mixture, with a SiO2/Na2O molar ratio of 2 and mixed with 10M sodium hydroxide, showed rapid early strength development. In contrast, the silica fume mixture (SSA), which used 123.58g of silica fume with 200mL of 10M sodium hydroxide solution, demonstrated slightly stronger performance after 28 days than commercial sodium silicate (SSC). GGBS-based pastes achieved approximately 72% of their 28-day strength in 7 days with SSA, while MK-based pastes reached 79%. Overall, the compressive strength tests suggested that silica fume can serve as a viable alternative to sodium silicate in geopolymer binders, enhancing their sustainability [23]. This study underscores silica fume's potential to improve the sustainability of geopolymer binders by utilizing industrial byproducts and reducing the environmental impact of construction materials.

In a study conducted, metakaolin was combined with an alkali activator comprising silica fume and sodium hydroxide, with silica fume content ranging from 0% to 25%. The Na_2O/Al_2O_3 molar ratio was adjusted between 0.8 and 1.2 by varying sodium hydroxide concentration, and specimens were cured at temperatures ranging from 60°C to 80°C. The study found that a higher Na_2O/Al_2O_3 molar ratio, specifically around 1, enhanced the dissolution rate of metakaolin during the hydrolysis reaction, resulting in increased availability of aluminate and silicate monomers for polycondensation. This led to higher compressive strength in specimens with a Na_2O/Al_2O_3 molar ratio of 1 compared to those with a ratio of 0.8 [24]. Additionally, silica fume contributed to improved microstructure and strength of the geopolymer matrix, although the optimal content varied based on specific application requirements. The study highlights the importance of adjusting the Na_2O/Al_2O_3 molar ratio and silica fume content, along with appropriate curing conditions, to optimize the mechanical properties of geopolymer pastes for various construction applications.

An investigation examined the impact of silica fume on the compressive strength of fly ash-based self-compacting geopolymer concrete (SCGC). Results showed that mixtures containing 5%, 10%, and 15% silica fume achieved higher compressive strengths compared to the control mix (0% silica fume) at all testing ages. For instance, at 28 days, mixtures with 10% silica fume surpassed the control mix by approximately 6.9% in terms of strength improvement. Silica fume's small particle size and spherical shape enable it to fill voids in the concrete matrix, resulting in a denser structure and refined microstructure, thereby enhancing mechanical properties [25]. This study underscores silica fume's significant role in improving the strength and durability of fly ash-based self-compacting geopolymer concrete through physical and pozzolanic reactions. The findings emphasize silica fume's potential as an effective additive for sustainable construction applications.

In conclusion, silica fume enhances the strength and durability of construction materials by filling voids and refining microstructures through physical and pozzolanic reactions. Studies demonstrate that incorporating silica fume improves the mechanical properties of geopolymer binders, leading to higher compressive strengths and reduced internal pores and cracks. Optimal silica fume content and curing conditions play crucial roles in maximizing strength development. Overall, these findings highlight silica fume as a valuable additive in construction, offering enhanced performance and sustainability benefits.

SEM AND EDS

Energy Dispersive X-Ray Microanalysis (EDX) is commonly used alongside scanning electron microscopy (SEM) to analyze the elemental composition of samples by detecting emitted X-rays from a high-energy electron beam. In recent studies on geopolymer concrete, SEM and EDX were employed to examine samples made with fly ash activated by sodium hydroxide, silica fume, and steel fiber. The analysis revealed Si/Al ratios ranging from 1.39 to 1.88, Na/Al ratios from 0.60 to 0.90, and Ca/Si ratios from 0.77 to 2.20, indicative of complex microstructures consistent with X-ray diffraction (XRD) results. Samples containing 20% silica fume (SF-20-20) exhibited flaky structures with Ca/Al ratios between 0.75 and 0.83, suggesting the presence of calcium-rich phases resembling CAH10 hydrates. The minimal presence of unreacted silica fume suggested complete dissolution and interaction with calcium aluminate cement (CAC), resulting in a dense microstructure and improved compressive strength with higher silica fume content. This underscores the importance of mix design optimization, particularly with silica fume, in achieving high-performance geopolymer concrete as a sustainable alternative to Portland cement.

In a similar study, SEM was utilized to compare 28-day cured geopolymer concrete specimens: one without silica fume (GPS0) and one with 5% silica fume (GPS5). SEM images revealed that GPS0 specimens exhibited a more porous structure with small cracks, indicating lower density and uniformity. Conversely, GPS5 specimens displayed a smoother and more consistent matrix, suggesting that silica fume enhanced concrete density by reducing voids and cracks, thereby improving strength and durability. This improvement was attributed to silica fume's promotion of additional pozzolanic reactions, contributing to a denser microstructure with fewer voids and cracks.

Another investigation compared alkali-activated slag concrete using two types of alkaline activators: sodium hydroxide and sodium silicate versus sodium silicate with silica fume. Findings showed that samples without silica fume exhibited numerous voids and pores, negatively impacting concrete permeability. However, incorporating 10% silica fume filled these voids and facilitated the formation of calcium silicate hydrate (C-S-H) gel, thereby reducing empty spaces and enhancing durability and mechanical properties. The addition of silica fume significantly improved the overall performance of alkali-activated slag concrete.

In summary, these studies collectively underscore the critical role of silica fume in enhancing the properties of geopolymer and alkali-activated slag concretes. Silica fume contributes to a more compact and uniform microstructure, reduces voids and cracks, and enhances compressive strength, permeability, and overall durability. These findings validate silica fume as an effective additive for producing high-performance, sustainable concrete, highlighting the importance of precise mix design for achieving superior concrete quality and longevity.

CONCLUSION

This paper studied discusses the potential of geopolymer concrete as an environmentally friendly alternative to traditional concrete in construction projects. It highlights the benefits of geopolymer concrete, such as lower greenhouse gas emissions, improved mechanical properties, and reduced reliance on Portland cement. The most important conclusions of the study are presented below:

i. Improved Strength: Silica fume enhances the compressive strength and overall durability of geopolymer concrete. Its fine particles effectively fill voids in the concrete matrix, resulting in stronger material compared to sodium silicate.
ii. Decreased Porosity: The inclusion of silica fume helps create a denser, more uniform microstructure by reducing voids and cracks, which contributes to better durability.
iii. Eco-Friendliness: Being an industrial by-product, silica fume reduces dependence on energy-intensive processes involved in sodium silicate production, supporting more sustainable construction methods.

iv. Reduced Carbon Emissions: The use of silica fume lowers greenhouse gas emissions, aligning with efforts to promote environmentally friendly construction practices.

In summary, silica fume not only enhances the performance of geopolymer concrete but also advances environmental sustainability. Future studies should aim to optimize its application and address any performance-related issues.

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