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Decarbonization Potential of Ultrafine Binder-Based Geopolymer Concrete in Sustainable Construction

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Abstract:

This study investigates the performance and decarburization potential of ultrafine binder-based geopolymer concrete (UFB-GPC) developed using ultrafine fly ash (UFFA) and ultrafine ground granulated blast furnace slag (UFGGBS) as sustainable alternatives to conventional Ordinary Portland Cement (OPC). The research focuses on evaluating the influence of varying percentages of UFGGBS replacement on workability, mechanical properties, durability, and microstructural behavior. Experimental results indicate a significant improvement in workability with increasing replacement levels, attributed to the ultrafine particle size and enhanced packing density of the binder system. Strength development and durability performance are found to be closely linked with the degree of geopolymerization and matrix densification. Comparative analysis with OPC-based concrete demonstrates superior performance and reduced environmental impact of UFB-GPC. Furthermore, life cycle assessment (LCA) results confirm a substantial reduction in CO_2 emissions due to the utilization of industrial by-products, highlighting the strong decarburization potential of the developed material. The study identifies optimal mix proportions that balance performance and sustainability, making UFB-GPC a promising solution for eco-friendly construction.

Keywords: Ultrafine binder, Geopolymer concrete, UFFA, UFGGBS, Workability, Mechanical properties, Durability, Microstructure, Geopolymerization, Sustainable construction, Carbon emission reduction, Life cycle assessment (LCA)

Introduction

The rapid growth of infrastructure and urbanization has significantly increased the demand for conventional concrete, primarily based on Ordinary Portland Cement (OPC). However, OPC production is highly energy-intensive and contributes nearly 7–8% of global CO_2 emissions, making it a major environmental concern. This has driven the need for sustainable and low-carbon alternatives in the construction industry. Geopolymer concrete (GPC) has emerged as a promising solution due to its ability to utilize industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), and other aluminosilicate materials, thereby reducing dependence on cement and minimizing carbon emissions. In recent years, the use of ultrafine binder materials, including ultrafine fly ash and ultrafine GGBS, has gained attention for enhancing the reactivity and microstructural properties of geopolymer systems. These ultrafine materials improve particle packing density, accelerate geopolymerization, and contribute to higher strength and durability. More importantly, their incorporation significantly enhances the decarbonization potential of geopolymer concrete by maximizing the utilization of industrial waste and reducing clinker consumption. Ultrafine binder-based geopolymer concrete not only offers improved mechanical performance but also supports sustainable construction practices through lower embodied energy, reduced greenhouse gas emissions, and efficient resource utilization. Therefore, understanding and evaluating the decarbonization potential of such advanced geopolymer systems is essential for developing eco-friendly construction materials and achieving global sustainability goals in the built environment.

Literature Review

The increasing environmental impact of Ordinary Portland Cement (OPC) production has led to extensive research on alternative binder systems, among which geopolymer concrete (GPC) has emerged as a sustainable solution. Studies indicate that geopolymer concrete, produced through the alkali activation of aluminosilicate materials such as fly ash and ground granulated blast furnace slag (GGBS), can significantly reduce CO_2 emissions by approximately 40–80% compared to conventional concrete This substantial reduction highlights the strong decarbonization potential of GPC in modern construction.

Several researchers have focused on the fundamental behavior of fly ash and slag-based geopolymer systems. Zhang et al. (2020) reported that FA/GGBS-based geopolymer concrete exhibits excellent mechanical properties, durability, and resistance to aggressive environments, making it a viable alternative to traditional concrete. However, challenges such as lack of standardized design codes and variability in raw materials still limit its widespread application

Recent advancements have emphasized the role of ultrafine binder materials in enhancing geopolymer performance. The incorporation of ultrafine slag and ultrafine fly ash improves particle packing, accelerates geopolymerization, and refines microstructure, leading to higher strength and durability. Experimental studies on self-compacting geopolymer concrete incorporating ultrafine slag have demonstrated significant improvements in both mechanical and durability properties due to enhanced reactivity and denser matrix formation

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Furthermore, developments in ultra-high-performance geopolymer concrete (UHPGPC) show that the use of finely processed materials such as silica fume, GGBS, and fly ash results in superior compressive strength, improved workability, and enhanced durability characteristics

These improvements are directly linked to the increased surface area and reactivity of ultrafine particles, which contribute to the formation of a dense aluminosilicate gel structure. From a sustainability perspective, the utilization of industrial by-products like fly ash and slag not only reduces landfill waste but also lowers embodied energy and carbon footprint. Studies have highlighted that the use of such materials supports circular economy principles and promotes resource efficiency in construction Additionally, the growing volume of industrial waste, particularly fly ash from thermal power plants, has further driven research into its effective utilization in geopolymer systems Despite these advancements, gaps remain in understanding the long-term performance, large-scale implementation, and life-cycle assessment of ultrafine binder-based geopolymer concrete. The variability in activator solutions, curing conditions, and material proportions also necessitates further research to optimize mix design and ensure consistency in field applications.

Parah Salsabeel Jalal et al (2025) was study the construction industry is one of the largest contributors to global carbon dioxide (CO_2) emissions, primarily due to the extensive use of Ordinary Portland Cement (OPC). According to Intergovernmental Panel on Climate Change, cement production alone accounts for approximately 7–8% of global CO_2 emissions. This environmental concern has accelerated research into sustainable alternatives such as geopolymer concrete (GPC), which utilizes industrial by-products like fly ash and ground granulated blast furnace slag (GGBS). The concept of geopolymer was first introduced by Joseph Davidovits in the 1970s. Geopolymer concrete is synthesized through the alkali activation of aluminosilicate materials, forming a three-dimensional polymeric network. Unlike OPC-based systems, GPC significantly reduces CO_2 emissions and exhibits superior resistance to chemical attack and high temperatures. Studies by researchers such as Hardhat and Rangan (2005) demonstrated that fly ash-based geopolymer concrete exhibits comparable compressive strength to conventional concrete, particularly under heat curing conditions. However, ambient curing remains a challenge due to slower reaction kinetics, especially in low-calcium fly ash systems.

Jonathan Oti et al (2024) geopolymers are inorganic, amorphous cementations materials that have emerged as a sustainable alternative to Ordinary Portland Cement (OPC) for greener concrete production. The use of geopolymer concrete promotes waste reutilization, as its precursor materials are often derived from

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agricultural and industrial by-products that would otherwise require disposal. This contributes to landfill reduction and enhances environmental sustainability. The present study focuses on the development of an eco-friendly sodium silicate alternative (SSA) synthesized from pumice powder (PP), replacing conventional commercial Na_2SiO_3 solution at a concentration of 10 M. A total of six geopolymer concrete mixes were prepared with varying alkaline-to-precursor (A/P) ratios of 0.1, 0.2, 0.3, 0.4, and 0.5. Among these, mix AF4 with an A/P ratio of 0.4 was identified as the optimum design. Despite achieving optimal proportions, the geopolymer mix exhibited lower compressive, split tensile, and flexural strengths compared to control OPC concrete.

Methodology

The methodology adopted in this study is designed to systematically evaluate the decarbonization potential of ultrafine binder-based geopolymer concrete (UFB-GPC) while ensuring its engineering feasibility for sustainable construction applications. This approach integrates experimental investigation, material characterization, performance evaluation, and environmental impact assessment to establish a comprehensive understanding of the behavior of UFB-GPC. Initially, ultrafine binder materials such as ultrafine fly ash (UFFA) and ultrafine ground granulated blast furnace slag (UFGGBS) are selected and characterized to assess their physical and chemical properties. Subsequently, geopolymer concrete mixes are developed using alkaline activators under controlled conditions, followed by preparation and curing of specimens. The study then focuses on evaluating fresh properties, mechanical strength, and durability performance through standardized tests. In addition, microstructural analysis is carried out to understand the geopolymerization mechanism and matrix densification. A key component of the methodology involves conducting a life cycle assessment (LCA) to quantify carbon emissions associated with UFB-GPC and compare them with conventional Ordinary Portland Cement (OPC) concrete. By combining experimental results with environmental analysis, the methodology aims to identify an optimal mix that achieves a balance between structural performance and reduced carbon footprint, thereby demonstrating the suitability of UFB-GPC as an eco-friendly alternative in modern construction.

Evaluating the decarbonization potential of ultrafine binder-based geopolymer concrete (UFB-GPC) involves an integrated experimental and analytical approach in which ultrafine fly ash (UFFA) and ultrafine ground granulated blast furnace slag (UFGGBS) are used as primary binders activated by alkaline solutions of sodium hydroxide (10–16M) and sodium silicate, with varying replacement levels (0–25%) of UFGGBS. The materials are first characterized through physical and chemical tests such as specific gravity, particle size analysis,. Concrete mixes are then designed by maintaining suitable alkaline liquid-to-binder ratios (0.35–0.50) and prepared through controlled mixing, casting, and curing under both ambient and oven conditions. Standard specimens are tested for mechanical properties including compressive strength, split tensile strength, and flexural strength at 7, 14, and 28 days, along with durability assessments such as water absorption, conducted to understand geopolymerization and matrix densification. The core of the study focuses on quantifying carbon emissions through a cradle-to-gate Life Cycle Assessment (LCA), where CO_2 emissions are calculated based on material quantities and their emission factors, and compared with conventional OPC concrete to determine percentage reduction and carbon efficiency. Finally, statistical analysis and performance indices are used to identify the optimum mix that achieves a balance between mechanical performance and minimum environmental impact, thereby establishing the suitability of UFB-GPC as a sustainable construction material.

Result and Discussion

The results and discussion section presents a comprehensive evaluation of the performance and sustainability benefits of ultrafine binder-based geopolymer concrete (UFB-GPC) developed using ultrafine fly ash (UFFA) and ultrafine ground granulated blast furnace slag (UFGGBS). This section aims to interpret the experimental findings in terms of workability, mechanical strength, durability characteristics, and microstructural behavior, along with their implications on carbon emission reduction. The influence of varying

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percentages of UFGGBS replacement on fresh and hardened properties is critically analyzed to identify trends and optimum mix proportions. Furthermore, the results are compared with conventional OPC-based concrete to assess relative improvements in performance and environmental impact. Special emphasis is placed on correlating strength development and durability performance with the degree of geopolymerization and matrix densification observed through microstructural studies. In addition, the life cycle assessment (LCA) results are discussed to quantify the reduction in CO_2 emissions achieved by replacing cement with industrial by-products, thereby highlighting the decarburization potential of UFB-GPC.

Workability

Workability in the context of ultrafine binder-based geopolymer concrete (UFB-GPC) refers to the ease with which the fresh concrete mix can be mixed, transported, placed, compacted, and finished without segregation or loss of uniformity. It describes the flow ability and consistency of the geopolymer mix, which is primarily influenced by the ultrafine particle size of binders such as ultrafine fly ash and ultrafine GGBS, the viscosity of alkaline activators, and the liquid-to-binder ratio. Unlike conventional OPC concrete, workability in UFB-GPC depends more on binder reactivity and chemical interactions rather than water content alone. Higher workability indicates better handling characteristics, improved compaction, and uniform distribution of materials, making the concrete more suitable for practical construction applications.

Table 1 Workability of ultrafine materials based geopolymer concrete

Percentages Replacement	Slump in mm
0%	65
5%	70
10%	80
15%	95
20%	100
25%	105

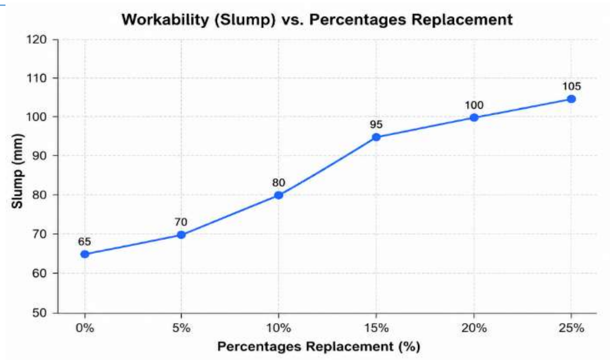

Figure.1. Workability of ultrafine materials based geopolymer concrete

The workability graph (slump vs. percentage replacement) clearly shows a continuous increase in slump value as the percentage of replacement increases from 0% to 25%. At 0% replacement, the slump is 65 mm, indicating relatively lower workability. As the replacement increases to 5% and 10%, the slump gradually rises to 70 mm and 80 mm, showing improved flow characteristics. A more significant increase is observed between 10% and 15%, where the slump jumps to 95 mm, indicating better lubrication and reduced internal friction in the mix. At 20% and 25% replacement, the slump reaches 100 mm and 105 mm, respectively, reflecting high workability and ease of placement.

Conclusion

The experimental results clearly demonstrate that the workability of ultrafine binder-based geopolymer concrete (UFB-GPC) significantly improves with an increase in the percentage of ultrafine GGBS replacement. The slump value consistently rises from 65 mm at 0% replacement to 105 mm at 25% replacement, indicating enhanced flowability and ease of handling. This improvement can be attributed to the finer particle size and better packing density of ultrafine materials, which reduce internal friction and promote a more cohesive mix. Additionally, the interaction between ultrafine binders and alkaline activators contributes to improved lubrication within the matrix. Based on the observed trend, mixes containing 20–25% replacement exhibit optimum workability suitable for practical construction applications, ensuring better compaction and uniformity without segregation. Thus, the incorporation of ultrafine materials not only enhances fresh properties but also supports the development of efficient and workable geopolymer concrete systems.

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