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Effects of Hybrid Fibers on Mechanical Behavior of Nanocomposites

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ABSTRACT

Geopolymers (GP) offers an environmentally friendly alternative to traditional cement, significantly reducing carbon emissions in concrete construction. However, the potential of Hybrid Fiber-Reinforced Fly Ash-based GP (HFGP) composites, which incorporate microfibers and nanoparticles, remains underexplored. This study aims to enhance the mechanical and microstructural properties of HFGP blends by adjusting the proportion of nano calcium carbonate. The HFGP was produced using 1% carbon fibers and 0.5% basalt fibers, with varying levels of calcium carbonate (1%, 2%, 3%, and 4%). Results showed that the HFGP blend containing 3% calcium carbonate exhibited the highest levels of hardness, compressive strength, fracture toughness, impact strength, and flexural strength.

KEYWORDS: Hybrid fibers; nanocomposites; nano calcium carbonate; compressive strength; hardness

1. INTRODUCTION

The production of ordinary Portland cement (OPC) contributes significantly to carbon emissions, posing a threat to environmental sustainability, with estimates attributing 10% of global CO_2 emissions to cement manufacturing [1, 2]. To mitigate this impact, reducing OPC usage in concrete is crucial. Geopolymers (GPs), which can replace OPC as a binding material, offer a promising solution [3-6]. By combining aluminosilicate materials like fly ash (FA) with an alkaline solution, GPs demonstrate their potential as effective binding agents [7]. However, to enhance their utility in concrete production, modern techniques must be employed to improve GP efficiency. Currently, GP's low flexural strength-to-weight ratio and brittleness limit its widespread use in the construction industry, where structural performance is critical [8]. Therefore, it is essential to develop efficient strategies to enhance the structural efficacy of GP mixtures. Incorporating micro-fibers and nanoparticles into GP mixes can reduce the need for cement in construction projects while improving their mechanical and microstructural efficiency, highlighting the importance of GPs for sustainable development.

In the construction industry, the use of nanoparticles to enhance composite materials has been extensively studied [9-12]. These studies demonstrate that adding nanomaterials can enhance the structural performance and durability of GP mixes by serving as nucleation sites for polymerization. While some research has explored the impact of nanoparticles on concrete, studies focusing on the effect of nanomaterials specifically on GP mix efficiency are limited [13, 14]. Previous studies have primarily investigated the use of titanium oxide [15, 16] or silica [17, 18] nanoparticles, with nano-calcium carbonate (calcium carbonate) receiving less attention. Studies have shown that adding 2% calcium carbonate is optimal for enhancing the mechanical and microstructural efficiency of GP mixes, although the impact of micro-fibers on this performance remains unexplored.

The synergistic effects of hybrid fiber-reinforced fly ash (FA)-based GP (HFGP) composed of hybrid fibers and calcium carbonate have not been thoroughly investigated. Understanding the efficacy of HFGP mixtures is crucial for their implementation in the building industry. This study analyzes the effects of various calcium carbonate concentrations on the mineralogical, mechanical, and microstructural characteristics of HFGP mixtures. The HFGP mixtures in this study consist of 1% carbon fibers and 0.5% basalt fibers, with varying percentages of calcium carbonate (0%, 1%, 2%, 3%, and 4%). The study examines the influence of increasing calcium carbonate levels on mechanical, thermal, microstructural, and toughness properties of HFGP. Parameters studied include hardness, stress-strain curves in compression, impact strength, and fracture toughness. The results will contribute to a better understanding and implementation of calcium carbonate-based HFGP mixtures in construction applications.

2. EXPERIMENTAL PROGRAM

2.1. Materials

This study employed Class F fly ash (FA) as the aluminosilicate precursor, which consists mainly of silica and alumina, as confirmed by chemical analysis. A binary activator (alkaline solution) for the hybrid fiber-reinforced fly ash-based geopolymer (HFGP) blends was created by mixing sodium silicate and sodium hydroxide. The sodium hydroxide obtained was 98% pure flakes, while the sodium silicate solution consisted of water (56.6%), sodium oxide (14.5%), and silica oxide (SiO_2) (28.9%). The HFGP mix was prepared with varying amounts of nano calcium carbonate (calcium carbonate) as detailed in Table 1.

The micro-carbon fibers used in this study have a modulus of elasticity of 242 GPa and a tensile strength of 4100 MPa, with a nominal length of 2 mm and a diameter of 7 µm. The basalt fibers, also employed in this investigation, possess an elastic modulus of 70 GPa and a tensile strength of 1800 MPa, with similar dimensions to the micro-carbon fibers.

Table 1: Characteristics of calcium carbonate

Property	Value	Property	Value
Color	White	Average size	15 – 40 nm
Dry extent (%)	97.5	pH	8-9
Moisture extent (%)	0.55	Bulk density	0.67 g/m^3

2.2. Sample Preparation and Testing

The study compares the HRD, FRT, and FRT of five different HFGP blends, which vary in the amount of nano calcium carbonate added to the fly ash (FA). All HFGP blends maintain a sodium silicate to sodium hydroxide ratio of 2.5 and an alkaline solution to FA ratio of 0.45. To create a 10 M alkaline solution, sodium hydroxide pellets are dissolved in water and stirred into the sodium silicate solution for 24 hours before preparing the HFGP mixes. Each HFGP mix includes 1% carbon fiber reinforcement and varying amounts (1%, 2%, 3%, or 4%) of calcium carbonate. Detailed compositions of each HFGP blend are provided in Table 2.

Table 2: Ingredients of all five mix designs

GP Mix	GP0NC	GP1NC	GP2NC	GP3NC	GP4NC
Sodium hydroxide (kg)	0.23	0.23	0.23	0.23	0.23
FA (kg)	1.8	1.8	1.8	1.8	1.8
Micro carbon fibers (wt. %)	1.0	1.0	1.0	1.0	1.0
Sodium silicate (kg)	0.58	0.58	0.58	0.58	0.58
Calcium carbonate (kg)	0	0.01	0.02	0.03	0.04

3. RESULTS AND DISCUSSION

3.1. Stress-Strain Curves

The introduction of calcium carbonate to an HFGP mix can significantly reduce the compressive strength (CST) at concentrations up to 2%, while concentrations of 3% lead to a substantial improvement. CST decreases by 3.3% for HFGP with 1% calcium carbonate (GP1NC) and by 13.1% for HFGP with 2% calcium carbonate (GP2NC) compared to the mix without calcium carbonate. This reduction may be due to insufficient calcium carbonate to act as a matrix filler between the HFGP and carbon fibers. However, adding 3% calcium carbonate increases CST by 17.2 percentage points in a 1% carbon fiber GP, suggesting that increasing calcium carbonate beyond 2% could be beneficial. The increase in CST after adding 3% calcium carbonate may be attributed to dense nanomaterials filling voids left by the calcium carbonate, accelerating the polymerization process for the GP. As the amount of calcium carbonate increases, cracks close, and the substance becomes denser, reinforcing the bond between hydration products and preventing nano-cracks, ultimately improving the strength of the HFGP blend. Therefore, 3% calcium carbonate is recommended for optimal CST in carbon HFGP mixes [19].

Figure 1 illustrates the stress-strain curves under compression of HFGP blends with varying percentages of carbon fibers and calcium carbonate. The presence of calcium carbonate reduces compressive stress, increasing the stiffness of the HFGP mix to withstand higher axial compressive loads at lower stresses. As the amount of calcium carbonate increases, the axial stress required to produce a given strain decreases, indicating increased axial stiffness. This effect is attributed to calcium carbonate acting as a nucleation site, contributing to denser HFGP mixes and faster polymerization. The brittleness of the mixes with calcium carbonate is also increased, leading to reduced CST at lower compressive loads. This increased brittleness is partly responsible for the higher post-peak stress in the stress-strain curves of the mixes with calcium carbonate.

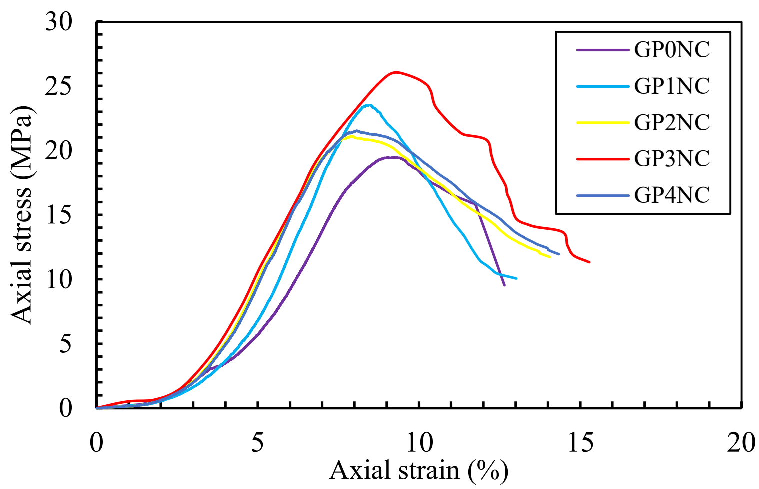

Figure 1: Effect of calcium carbonate concentration on compressive stress-strain efficiency of HFGP mix

3.2. Fracture Toughness

Fracture Toughness (FRT) measures a material's ability to withstand crack propagation. Figure 2 illustrates FRT values for five HFGP blends with 0%, 1%, 2%, 3%, and 4% calcium carbonate. Previous studies have shown that FRT values in HFGP blends with calcium carbonate are higher than in GP0NC. All samples exhibit FRT values above 0.4 MPa.m1/2, irrespective of the calcium carbonate content. The addition of carbon fibers, contributing to a stiffer matrix, likely enhances FRT by improving the material's resistance to fracture formation and growth. Additionally, carbon fibers help transmit stress within the HFGP mix, further improving FRT.

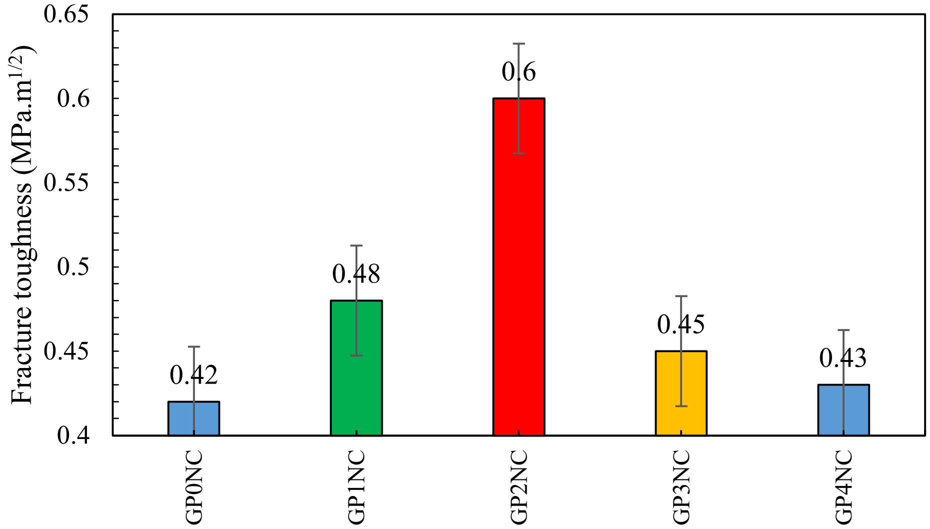

Figure 2: Increasing the percentage of calcium carbonate

In the HFGP blends, increasing the calcium carbonate content from 1% to 2% consistently improved the FRT, with the highest FRT observed at 2% calcium carbonate (0.6 MPa.m1/2). All HFGP blends containing calcium carbonate exhibited higher FRT than those without, indicating that calcium carbonate enhances the toughness of the mixes. Specifically, the 1% calcium carbonate sample showed a 14% increase in FRT compared to the calcium carbonate-free control, while the GP2NC sample had a 42.9% higher FRT than the control. However, at 3% calcium carbonate, FRT was significantly reduced compared to 1% or 2%. GP3NC showed a 7.1% increase in FRT over the control, and GP4NC exhibited a 2.4% increase. The presence of calcium carbonate nanoparticles may improve the interface between the HFGP matrix and carbon fibers, reducing the bridging effect of the fibers and improving FRT. This nanoparticle integration enhances adhesion within the HFGP mix, resulting in a denser, tougher, and more crack-resistant product, while also accelerating polymerization and strengthening the microstructure of the HFGP mix [26].

3.3. Hardness

Hardness (HRD) measures the HFGP blend's resistance to localized plastic deformation. Figure 3 illustrates the impact of adding 0%, 1%, 2%, 3%, and 4% calcium carbonate to carbon HFGP blends. The addition of 1% and 2% calcium carbonate decreased HRD, while 3% and 4% calcium carbonate slightly improved HRD, with 3% being the most effective. Compared to the GP0NC control, GP1NC showed a 10.8% lower HRD, and GP2NC had a 2.4% lower HRD. GP3NC exhibited a 2.9% increase in HRD over the control, while GP4NC showed a 1.3% increase, aligning with the control group. The transfer of internal stress from the HFGP matrix to the nanoparticles along a wide interfacial area may contribute to the increased HRD, as calcium carbonate particles are known for their high strength. Filling gaps between chains with nanoparticles enhances the HFGP mix's resistance to distortion and fracture propagation. A recent study defined 80 HRD as the baseline for an HFGP blend without nanoparticles and fibers [28]. Since carbon fiber has been shown to positively affect HRD (> 80 HRD), its presence in the HFGP mix likely influenced these results.

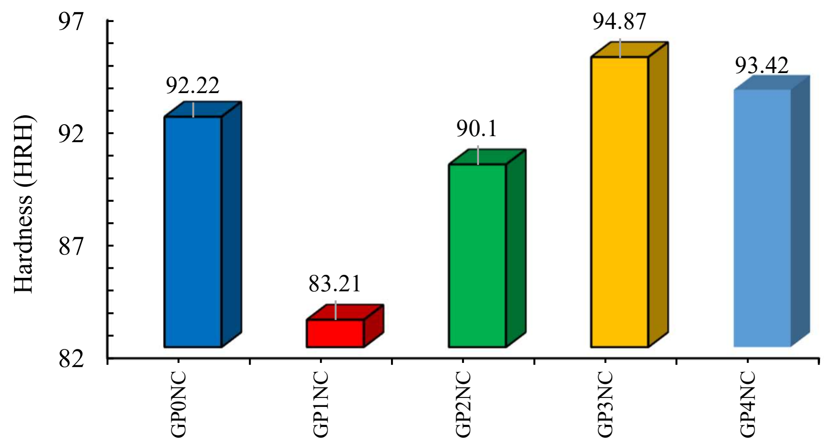

Figure 3: HRD values of HFGP mix for different extents of calcium carbonate

3.4. Impact Strength

Figure 4 illustrates the Impact Strength (IST) of various HFGP mixes with different amounts of calcium carbonate. The addition of calcium carbonate particles increases the IST of the HFGP blend, as indicated by experimental data. Specifically, the IST is higher in an HFGP matrix with 2% calcium carbonate compared to one without it, suggesting that using 2% calcium carbonate in a carbon-free graphite powder matrix blend is optimal for IST. As expected, the IST of the GP1NC sample is only 0.3% higher than that of the GP0NC sample. However, the IST of the sample with 2% calcium carbonate is remarkably 176.3% higher than that of the control group with no calcium carbonate (GP0NC). Similarly, compared to GP0NC, GP3NC exhibits a 5.7% increase in IST, while GP4NC shows a 0.8% increase. The aggregation of nanoparticles may cause fractures in the HFGP mix, but stronger connections between microcarbon fibers and HFGP components likely contribute to the observed increase in durability [26].

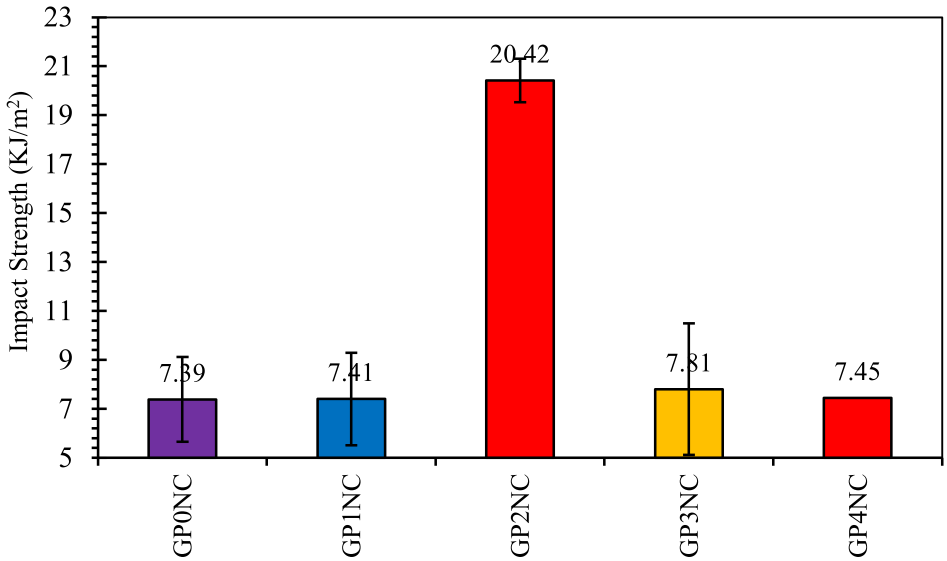

Figure 4: The HFGP blend's IST values at different concentrations of calcium carbonate

The effectiveness of the HFGP matrix relies on the transmission of load among nanoparticles. The interfacial toughness between the matrix and calcium carbonate is crucial for this load-transferring function. Carbon fibers increase binding strength and act as a bridge between components, enhancing load transmission and the interface. A larger interfacial area improves load transfer and impact strength (IST). Both calcium carbonate and carbon fibers contribute to boosting the impact energy of carbon HFGP mixes with different calcium carbonate concentrations.

4. CONCLUSIONS

This study aims to investigate the influence of varying calcium carbonate levels on the mechanical and microstructural properties of an HFGP blend with hybrid microfibers. Key findings include:

1. The addition of 3% calcium carbonate resulted in a notable 17% increase in compressive strength compared to the control without calcium carbonate. This improvement is attributed to calcium carbonate expediting polymerization and the strong bridging effect of hybrid carbon and basalt fibers.
2. Incorporating 2% calcium carbonate led to a significant 43% enhancement in fracture toughness compared to the control. This improvement is likely due to the presence of micro-carbon fibers and the effective filling capacity of calcium carbonate, aiding in stress transmission and crack prevention.

3. The impact strength of the HFGP blend was improved by the addition of calcium carbonate, creating a denser matrix that resists crack formation due to enhanced bonding between micro carbon fibers and other components.

In the construction industry, reducing cement usage is essential for sustainability due to its significant carbon footprint. HFGP blends with nano calcium carbonate show promise as cement substitutes, especially with micro- and nanoparticles. The studied HFGP exhibits excellent mechanical and fracture properties, indicating its potential for sustainable concrete construction in the future.

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