Uluslararası İleri Doğa Bilimleri ve Mühendislik Araştırmaları Dergisi
Sayı 8, S. 264-269, 10, 2024

Araştırma Makalesi

International Journal of Advanced Natural Sciences and Engineering Researches
Volume 8, pp. 264-269, 10, 2024

Research Article

https://as-proceeding.com/index.php/ijanser
ISSN:2980-0811

Amelioration of Compressive Stress-Strain and Flexural Behavior of Fiber-Reinforced Eco-Friendly Nanocomposites for Sustainable Development

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(Received: 18 November 2024, Accepted: 26 November 2024)

(2nd International Conference on Trends in Advanced Research ICTAR 2024, November 22-23, 2024)

ATIF/REFERENCE: Safi, S. A., Raza, A., Khan, N. & Selmi, A. (2024). Amelioration of Compressive Stress-Strain and Flexural Behavior of Fiber-Reinforced Eco-Friendly Nanocomposites for Sustainable Development. *International Journal of Advanced Natural Sciences and Engineering Researches*, 8(10), 264-269.

Abstract **–** Geopolymer (GP) mortars offer a highly suitable alternative to cement for sustainable and eco-friendly construction within the concrete industry. To apply fiber-reinforced (FRF) GP mortars practically, it's crucial to enhance their mechanical and microstructural properties through the inclusion of micro-fibers and nano-particles. This study focuses on improving the mechanical performance of micro basalt-FRF fly ash-based GP mortars by incorporating varying dosages of nano-Titania. Four distinct levels of Titania (from 1% to 4%) were tested to produce GP mortars containing 2 wt.% micro-basalt fibers (MBF). A control sample without Titania added and containing 2% MBF was also made for comparison. Results from this study showed that adding 3% Titania to the micro basalt-FRF-GP mortar led to improvements of 28.06 in compressive strength, 61.4% in flexural strength, and 8.5% in elastic modulus. Therefore, incorporating Titania effectively enhances the mechanical properties of FRF-GP mortar.

Keywords – Mechanical Performance; Micro-Fibers; Nanocomposites; Compressive Strength, Nanoparticles.

I. INTRODUCTION

The cement industry's significant carbon emissions are a major challenge to environmental sustainability. Geopolymers (GP) offer a promising alternative to Portland cement in binding applications for concrete construction, thanks to their distinctive properties [1-5]. GP mortar acts effectively as a binder in mortars that can be produced by activating aluminosilicate materials, such as fly ash, with an alkaline solution [6-12]. Over time, studies have shown that GP materials demonstrate structural characteristics comparable to, or even surpassing, those of conventional concrete [13-15]. However, to expand the practical use of GP mortars in concrete production, substantial improvements in GP behavior are essential, achievable through advanced methods. Additionally, GP materials often exhibit lower early strength and increased brittleness, which limits their application in the construction industry, especially in areas requiring higher flexural strength (FS) [16]. Therefore, developing efficient and innovative techniques to enhance the structural characteristics of GP mortars is crucial. Nano-particles and micro-fibers could play a vital role in improving both the mechanical and microstructural properties of GP mortars.

A comprehensive literature review reveals a gap, as no studies have explored the combined effects of micro basalt fibers (MBF) and Titania on the mechanical and microstructural characteristics of Geopolymer mortar. The present research evaluates the influence of various concentrations of Titania on the mechanical properties of GP mortars reinforced with basalt fibers (FRF). In this research, Geopolymer mortars were prepared with 2% MBF and varying Titania contents (0%, 1%, 2%, 3%, and 4% by weight). The impact of these different Titania dosages was assessed on key mechanical characteristics of GP, comprising the GP mortar's FS, compressive strength-strain behavior, elastic modulus (EM), and compressive strength (CS).

II. TESTING PROGRAM

i. Materials

In this study, nano-Titania (P25, with a composition of 75% anatase and 25% rutile) with particle sizes between 1 and 30 nm is utilized. Titania's primary composition is 99.68% TiO_2. Table 1 outlines the characteristics of Titania used in different proportions for the production of GP mortar. The MBF implemented here has a tensile strength of 1800 MPa and an elastic modulus of 70 GPa. MBF dimensions include a nominal length of 2 mm and a diameter of 7 μm.

Table 1. Features of Titania

Property	Value	Property	Value
Specific gravity	0.25 g/cm^3	Ratio of anatase to rutile	80: 20
Median particle size	21 nm	Shape	spherical
Content of Titania	99.7%	LOI	< 0.03

In this study, class F fly ash serves as the aluminosilicate precursor, with its chemical properties detailed in Table 2. A combination of sodium silicate and NaOH functions as the binary activator to synthesize the GP mortars. NaOH is sourced in flake form with 98% purity, while sodium silicate is provided as a solution. This sodium silicate solution includes 30% SiO2, 12.5% Na2O, and 57.4% H2O.

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Table 2. Composition of fly ash

Compound	Composition (%)	Compound	Composition (%)
SiO_2	59.11	Na_2O	0.82
Al_2O_3	24.42	MgO	0.63
CaO	1.54	SO_3	0.16
Fe_2O_3	5.94	LOI	1.31
K_2O	2.91	-	-

Five different types of GP were created, each containing varying levels of Titania by mass of fly ash, and tested for CS, FS, EM, FT, TM, and HN. An alkaline solution-to-fly ash ratio of 0.45 was used, while the sodium silicate-to-NaOH ratio remained constant at 2.5 across all GP mortars [1]. Sodium hydroxide granules were dissolved in water and then stirred into the Na_2SiO_3 mixture 24 hours prior to GP mortar preparation to ensure an alkaline solution concentration of 12 M. Each GP mortar was reinforced with 2% MBF, with Titania incorporated at dosages of 1%, 2%, 3%, and 4%, respectively. The content of NaOH (kg) was 0.25, content of Sodium silicate (kg) was 0.57, content of Fly ash (kg) was 1.8, and the content of MBF (wt. %) was 2.0 in all mixes.

ii. Development of Specimens

A Hobart mixer is used for preparing GP mortars. During the mixing process, fly ash and MBF are first dry-mixed at a low speed for 5 minutes. Once this initial dry mixing is complete, the alkali solution, containing varying amounts of Titania, is added and mixed at high speed. This continues until a uniform

GP mortar is achieved. The fresh mortar is then poured into molds and cured at 80°C for 24 hours. Afterward, it is removed from the molds and, to improve its mechanical qualities, left to cure for a further 28 days at room temperature.

III. RESULTS AND DISCUSSIONS

i. Strength-Strain Behavior

Figure 1 illustrates the compressive strength-strain response of GP mortars with Titania contents of 0%, 1%, 2%, 3%, and 4%, each containing 2% MBF. The control sample (BGP-0%NTO) exhibited lower axial stiffness compared to Titania-enriched specimens, indicating that adding Titania enhances axial strength, making the GP mortar more rigid and able to withstand higher compressive loads at reduced strain levels. The compressive strength-strain curves also show that increasing Titania levels improves axial strength values while lowering axial strain values. This could be due to the denser GP matrix and the accelerated polymerization process induced by Titania, as it acts as a nucleation site, forming additional products within the GP matrix [1-3], which contributes to higher stiffness. Furthermore, samples with varying Titania levels showed greater reductions in CS at lower strains. This may result from the increased axial stiffness prior to post-collapse, which leads to failure in the post-peak region of the strength-strain curves, reflecting the more brittle nature of Titania-modified GP mortars.

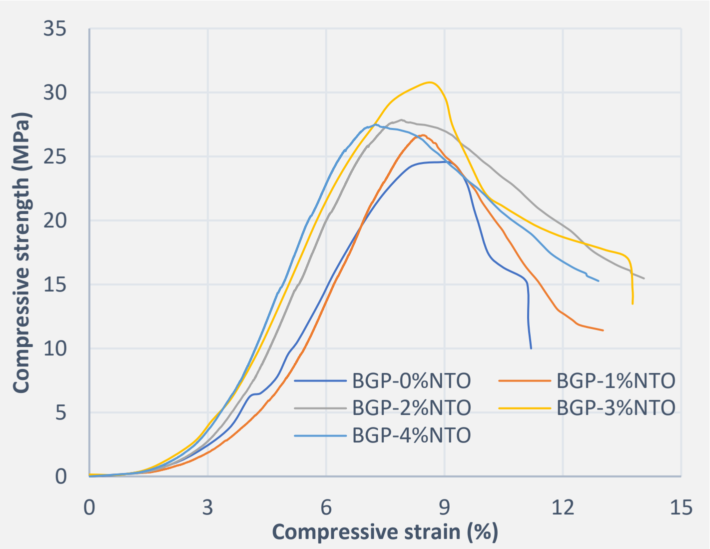

Figure 1. Behavior of FRF-GP mortar's compressive strength and strain with varying titanium doses

ii. Elastic Modulus

Because of the greater axial stiffness in the GP mortars, the specimens with different percentages of Titania showed steeper strength-strain gradients. As a result, these mortars' EM values exceeded those of BGP-0%NTO, as Figure 2 illustrates. In particular, BGP-1%NTO's EM was 2.2% more than that of BGP-0%NTO, which had Titania absent but 2% MBF. Likewise, BGP-2%NTO's EM was 5.8% more than Titania-free BGP-0%NTO's. In comparison to BGP-0%NTO, which likewise included 2% MBF but no Titania, the EM of BGP-3%NTO rose by 8.5%. Similarly, BGP-4%NTO's EM was 6.7% higher than BGP-0%NTO's with 2% MBF and no Titania content. As a result, the specimen with 3% Titania demonstrated the highest axial stiffness, reaching the peak EM of 635 MPa. The enhanced elastic moduli of mortars containing Titania may be due to the formation of a denser matrix and the accelerated polymerization process in GP mortar facilitated by Titania, which likely serves as nucleation sites, promoting the development of additional products within the GP matrix [1-3].

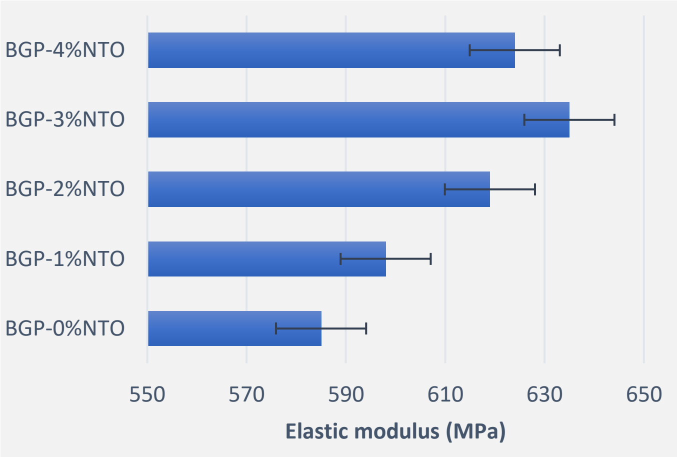

Figure 2. Elastic moduli of FRF-GP mortar with varying Titania doses

This paragraph examines the link between the compression elastic modulus and CS in GP mixes. The two parameters exhibit a consistent linear relationship, with the elastic modulus increasing proportionally as CS improves. This suggests that increasing the amount of nano-Titania improves the compressive stress-strain curve's linear elastic region's slope. The relationship between the elastic modulus and CS of GP is seen in Figure 3.

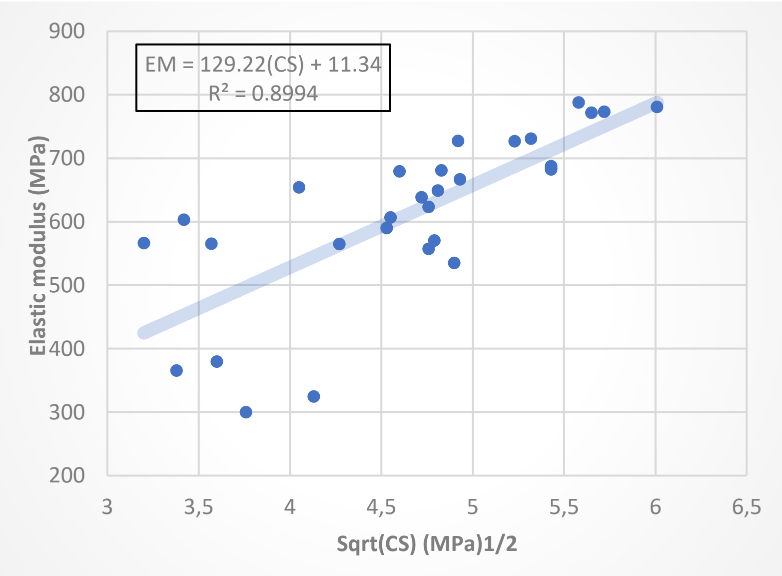

Figure 3. The connection between CS and the GP mix's elastic modulus

iii. Flexural Strength

The effect of adding 2% MBF and different concentrations of Titania (0%, 1%, 2%, 3%, and 4%), to GP mortar on its FS is shown in Figure 4. A mortar material's FS shows how well it can support flexural loads. Based on six samples from each GP mortar mix, the average FS results indicate that FS rose with Titania concentration up to a dosage of 3% before declining. The FS dropped but stayed above the control mortar's level when 4% Titania was introduced. The aggregation of MBF and nanoparticles may be the cause of this decrease [4]. However, as demonstrated, the FS was still greater than that of the control mortar (BGP-0%NTO), most likely as a result of these mortars' greater bending load capability in Figure

4. The improvement in FS may stem from enhancements in the microstructure from the Titania addition, which accelerated the polymerization reaction in the GP mortar, resulting in a denser matrix.

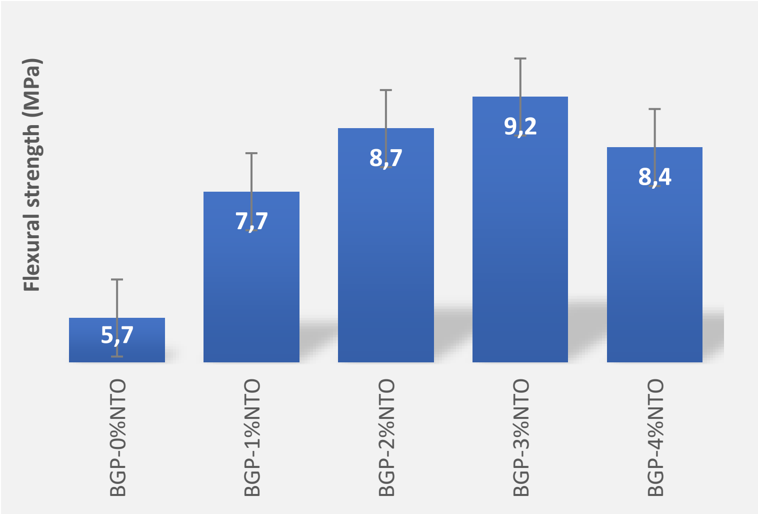

Figure 4. FRF-GP mortar's FS and bending loads for varying titanium doses

Aggregation and clustering of nanoparticles may be the cause of the observed decrease in the FS of GP with higher Titania concentrations above 3%. Comparable results for ordinary GP mortars with up to 3% titanium have been documented in the literature [5]. The incorporation of 1% and 2% Titania also led to a reduction in FS without the addition of MBF, as shown in a prior study [5]. However, GP mortars containing 2% MBF exhibited enhanced FS at all Titania levels (1%, 2%, 3%, and 4%) when compared to BGP-0%NTO. The highest FS was achieved with 3% Titania. A previous investigation demonstrated that the inclusion of Titania at 1% and 2% in GP mortar resulted in improvements in flexural strength by 5.6% and 44.5%, respectively [6]. In contrast, in the current study, the addition of 1%, 2%, and 3% Titania resulted in FS enhancements of 35%, 52.63%, and 61.4%, respectively. This suggests that combining Titania with MBF reinforcement is more effective in increasing FS than using Titania alone. In comparison to the control mortar with 2% MBF and no Titania, the FS of GP mortars with 1%, 2%, 3%, and 4% Titania and 2% MBF were 135%, 152.63%, 161.4%, and 147.37%, respectively.

IV. CONCLUSION

Assessing the mechanical and fracture properties of micro-basalt FRF-GP mortar with different concentrations of nano-Titania was the goal of the current experimental investigation. The following key observations were made from the research:

1. The highest compressive strength (CS) for basalt-FRF-GP mortars was attained by incorporating 3% Titania, which resulted in a 28.06% increase compared to the control mortar without Titania. This improvement may be due to the ability of nano-particles to hinder crack formation, as well as Titania's role in enhancing the polymerization rate of the GP mortar. The highest elastic modulus was observed with 3% Titania and 2% MBF, which was 8.5% greater than the control mortar.
2. 3% Titania was found to have the highest flexural strength (FS), which was 61.4% higher than that of the control mortar. Titania's better microstructure and the GP mortar's quicker polymerization, which resulted in increased densification, are responsible for this improvement in FS. 3% Titania and 2% MBF produced the maximum toughness modulus, which was 66.3% more than that of the control mortar. This increase might be related to the GP mortar's increased rigidity as a result of Titania and MBF working together.

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