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Mechanical Performance of Microfiber-Reinforced Geopolymer Mortar with Nano-Titania

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Abstract – Geopolymer (GP) mortars are highly acknowledged in the concrete industry as superior cement alternatives, providing an environmentally benign and sustainable building solution. Micro-fibers and nanoparticles are crucial for improving the mechanical characteristics of fiber-reinforced (FRF) GP mortars and expanding their practical application. By adding different amounts of nano-Titania, this work seeks to enhance the mechanical behaviour of GP mortars based on micro basalt-FRF fly ash. Two weight percent of micro-basalt fibres (MBF) are added to GP mortars together with four different titanium doses (varying from 1% to 4%). For comparison, a control model with 2% MBF and no Titania is also created. According to the findings, micro basalt-FRF-GP mortar's toughness modulus, flexural strength, elastic modulus, and compressive strength are all increased by 27%, 61%, 8%, and 66%, respectively, when 3% titanium is added.

Keywords – Geopolymer Mortar; Micro-Basalt Fibers; Nano-Titania; Compressive Strength; Toughness Modulus

I. INTRODUCTION

This Cement production has a large carbon footprint and has grown to be a major source of pollution worldwide in recent decades. Because of their superior binding qualities, geopolymers (GP) are being suggested more and more as workable substitutes for Portland cement in the production of concrete [1]. Fly ash (FA) and other activated aluminosilicate materials can be combined with an alkaline solution to create these mortars [2]. The usage of GP has demonstrated increased structural performance over time, in contrast to standard concrete [3-5]. However, sophisticated methods are required to improve the usefulness of GP mortars in concrete. Even yet, GP mortars have a tendency to behave brittlely and have a lower initial strength, which restricts their application in the construction sector where a relatively high flexural strength (FS) is needed [6]. Thus, it is imperative to apply sophisticated techniques to improve the structural performance of GP mortars by adding both nanoparticles and micro-fibers. At the microstructural level, these changes could greatly enhance the mechanical and structural behaviour of GP mortars.

Numerous investigations have shown that GP mortars with fibre modifications operate mechanically better than those without [2, 6–8]. The successful application of micro-basalt fibres (MBF) to reduce micro-cracking and improve energy absorption during the pull-out process is responsible for this improvement in mechanical behaviour [9]. It has been demonstrated that GP mortars treated with fly ash-derived micro-MBF increase setting time, decrease dry shrinkage, and improve compression strength (CS) [10]. According to one study, for instance, adding 10 weight percent microfibers raised the CS of GP mortar by 37% [11].

In the construction industry, nanoparticles have grown in significance as a means of improving mortar performance. It has been discovered that adding smaller amounts of nanomaterials can significantly increase the GP mortars' structural performance and longevity. This enhancement is explained by the ultra-fine size of the nanoparticles, which uses nano-fillers and nucleation sites to speed up geopolymerization. Nanomaterial-modified mortars have improved compression characteristics, flexural and early-age performance, microstructural properties, impact resistance, and electrical characteristics, according to recent studies on the mechanical and microstructural aspects of cementitious mortars [12–16].

Despite these advancements, little study has been done on using MBF and titania together to improve the mechanical performance of GP mortar. The purpose of this study is to examine the effects of varying nano-Titania percentages on the mechanical characteristics of basalt-fiber-reinforced (FRF) GP mortars. In order to examine the effects of increasing amounts of Titania (0% to 4% by weight, in 1% increments) on toughness modulus (TM), compressive strength (CS), flexural strength (FS), elastic modulus (EM), and strength-strain behaviour under compression and flexure, GP mortars were synthesised with 2% MBF. The results of this research will be helpful to structural designers who want to build concrete structures that are sustainable.

II. MATERIALS AND METHOD

A. Materials

In the current study, nano-Titania (P25, 25% rutile, and 75% anatase) with a grain size range of 1–30 nm was utilised. 99.68% Titania is the main component of titania. The study employed an additional MBF with nominal dimensions of 2 mm and 7 μm, respectively. Its elastic modulus and tensile strength were measured at 70 GPa and 1800 MPa, respectively. In the current investigation, class F-FA was employed to fill its role as a precursor for aluminosilicate. Table 1 presents the molecular composition of FA. The binary activator made of sodium silicate and NaOH was utilised to make the GP mortars. Flakes of 98% pure NaOH were acquired, while sodium silicate was in the solution form comprising three major constituents including 57.4% H_2O, 30% SiO_2, and 12.5% Na_2O.

Table 1. Composition of fly ash

Compound	**Composition (%)**	**Compound**	**Composition (%)**
Fe_2O_3	4.99	Na_2O	0.81
Al_2O_3	25.4	SO_3	0.15
K_2O	1.95	MgO	0.64
SiO_2	60.1	LOI	1.39
CaO	2.58	-	-

In order to conduct the investigation, five distinct GP mortar mixtures with varied ratios of titanium to fly ash (FA) mass were created and tested. These mixes' toughness modulus (TM), elastic modulus (EM), flexural strength (FS), and compressive strength (CS) were examined. For all of the mixes in the GP mortar production, a constant alkaline solution to FA ratio of 0.45 and a sodium silicate to NaOH ratio of 2.50 were employed [13]. Before the GP mortars were made, NaOH pellets were dissolved in water and added to the sodium silicate solution. In order to guarantee the formation of a 12 M alkaline solution, this procedure started 24 hours prior to the GP mortar manufacturing. Additionally, 2% micro basalt fibres (MBF) were added to these mortars, and titanium was added in increments of 1%, 2%, 3%, and 4%. Table 2 displays the mortar mix design in detail.

Table 2. Mortar design of all five mortars

GP Mortar	BGP-0%NTO	BGP-1%NTO	BGP-2%NTO	BGP-3%NTO	BGP-4%NTO
NaOH (kg)	0.23	0.23	0.23	0.23	0.23
Sodium silicate (kg)	0.58	0.58	0.58	0.58	0.58
Fly ash (kg)	1.8	1.8	1.8	1.8	1.8
MBF (wt. %)	2.0	2.0	2.0	2.0	2.0
Titania (kg)	0	0.01	0.02	0.03	0.04
Titania (wt. %)	0	1.0	2.0	3.0	4.0

B. *Development of specimens*

Using a Hobart mixer, fresh GP mortars were made by first dry mixing fly ash (FA) and micro basalt fibres (MBF) for five minutes at a low speed. After these components had been well combined by dry means, an alkaline solution containing different titania concentrations was added and quickly stirred until the GP mortar was completely homogeneous. After that, the freshly created mortars were cured at 80°C in moulds. To guarantee better mechanical performance, the specimens were demolded and allowed to cure at room temperature for the following 28 days after maintaining the temperature curing for twenty-four hours.

Thirty cubical samples, each measuring 20 mm x 20 mm x 20 mm, for five different GP mortars made up the test matrix for this study. In accordance with ASTM D 695 [17], these samples were created and compressed until related damages occurred. For every GP mortar, six samples were examined, and the samples' compressive strength (CS) was noted at 0%, 1%, 2%, and 3% titanium, respectively. In this study, the average CS results of the five groups—each with six samples—are presented and examined. The peak load-carrying capacity of the samples under consideration was divided by the corresponding gross area to determine the CS of the samples.

The same methodology used for the CS study was used to evaluate the flexural strength (FS) of six samples, each measuring 60 mm by 20 mm by 20 mm, at 0%, 1%, 2%, and 3% Titania, respectively. Three-point flexural tests were performed on fabricated specimens containing 0%, 1%, 2%, 3%, and 4% titania in accordance with ASTM C-293 [18] criteria. In this study, the average FS results of the five groups—each with six samples—are presented and examined. Using a displacement-controlled method, the samples were loaded at a rate of 1 mm/min. The ultimate flexural loading was obtained from the flexural strength-strain plot and utilised to compute the FS depending on the specimens' span and size.

III. Analysis of Results

A. *Compressive Strength*

Pa Figure 1 shows how the compressive strength (CS) of GP is affected by adding varying percentages of titania (0%, 1%, 2%, 3%, and 4%) to GP mortar containing 2% MBF. According to the study, CS significantly improved up to 3% Titania; after that, CS decreased. GP mortars modified with 1% (BGP-1%NTO) and 2% (BGP-2%NTO) Titania shown improvements in CS of 11% and 17%, respectively, in comparison to GP mortars without Titania. In a similar vein, GP mortar that had been altered with 3% Titania and 2% MBF showed a 27% rise in CS. GP polymerization is accelerated by the nanoparticles' capacity to fill holes, which is why CS has improved. However, because of fewer items, additional rises in Titania resulted in an 18% decrease in CS.

Titania-based GP mortars have faster polymerization, which may be related to nucleation sites that generate extra products. Furthermore, Titania reduced cracks and produced denser mortars by filling in the spaces between FA particles to create a denser matrix. As a result, during GP hydration, there was strong bonding between the products, which prevented nano-cracking and produced high strength. Thus, for basalt FRF-GP mortar, 3% Titania showed the best CS results.

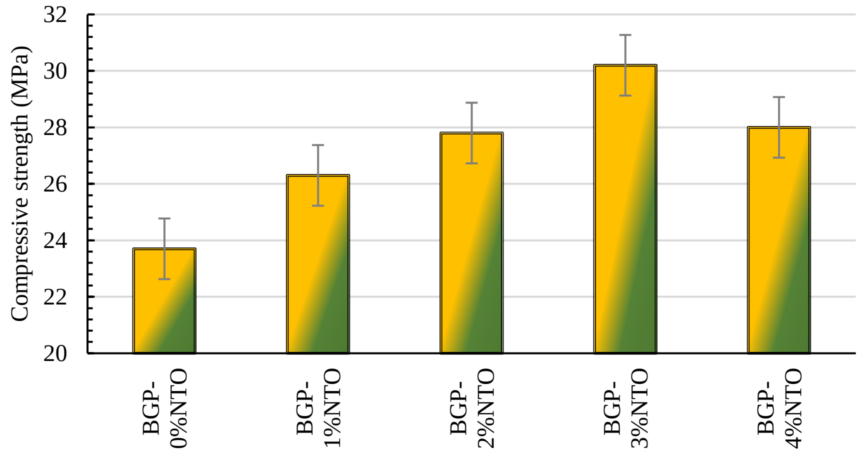

Fig 1. CS and compressive loads of FRF-GP mortar for different dosages of Titania

The CS of GP mortars containing Titania (0%, 1%, 2%, 3%, and 4%, in that order) with zero MBF was lower than that of Titania-modified GP mortars with MBF [22]. This clearly confirms that the performance of 2% MBF addition in GP mortars modified with titania is valid. As seen in Figure 1, the denser microstructure of the mortars at the chosen proportion of nanoparticles may be the cause of the observed increase in related CS of Titania-modified GP mortars. In conclusion, greater concentrations of Titania and MBF can be added simultaneously to achieve superior CS. Consequently, employing modified GP mortars at 1%, 2%, 3%, and 4% that contained 2% MBF revealed 111%, 117%, 127%, and 118% of the CS of the reference mortar sample that contained 2% MBF and 0% Titania.

B. *Strength-Strain Behavior under Compression*

Figure 2 displays the strength-strain behavior of GP mortars subjected to compression loading with 0%, 1%, 2%, 3%, and 4% Titania having 2% MBF. In contrast to Titania-modified GP mortars, reference BGP-0%NTO specimen showed reduced axial stiffness showing that Titania modification increases the axial strength of GP mortars by increasing the stiffness enough to withstand enhanced axial loadings at lower compression strain levels. The strength-strain plot for compressive loads shows enhancement in axial strength results with augmented percentages of Titania at corresponding lower axial strains. This behavior firmly substantiates the accelerated pace of the GP mortars polymerization as obtained with Titania inclusion to develop potential nucleation sites for associated supplementary products [19-21] showing higher stiffness. Also, the specimens containing varying amounts of Titania revealed a notable loss of CS at lower values of compressive strain. This reduction might be ascribed to the higher axial stiffness of specimens before the post-collapsing stage, which damaged the GP mortars during the post-peak region of strength-strain plots due to the larger brittleness of the mortars modified with Titania.

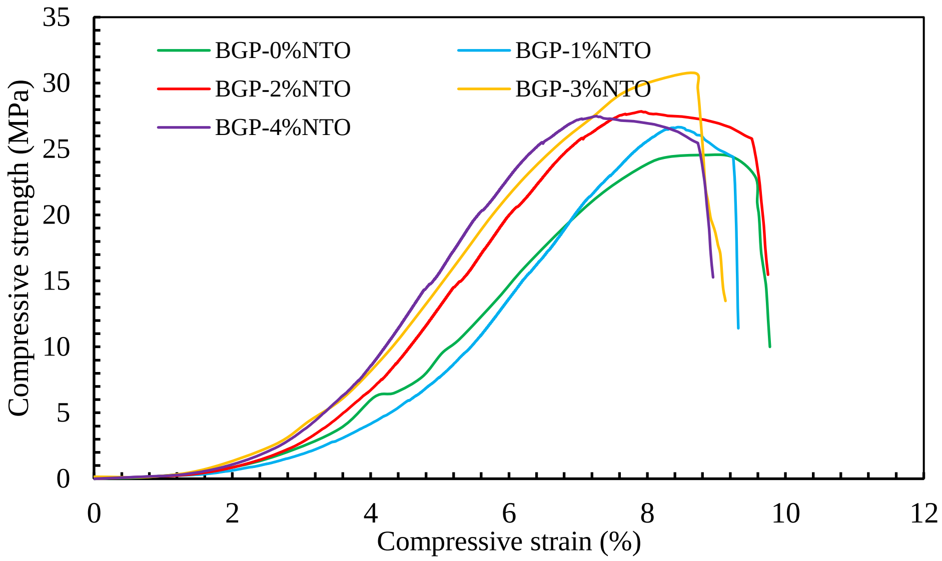

Fig 2. Compressive strength-strain behavior of FRF-GP mortar for different dosages of Titania

C. *Elastic Modulus*

The specimens comprising different amounts of Titania revealed enhanced gradients of strength-strain plots due to the larger axial stiffness of the GP mortars. In contrast to the EM of the BGP-0%NTO mortars, the EM of such Titania-modified mortars was higher as presented in Figure 3. The EM of specimen BGP-1%NTO was 2% higher than BGP-0%NTO having 2% MBF with zero Titania. Similarly, the EM of specimen BGP-2%NTO was 6% larger than BGP-0%NTO without Titania. The EM of specimen BGP-3%NTO was 8% larger than BGP-0%NTO having 2% MBF and no Titania. Equally, the EM of specimen BGP-4%NTO was 7% larger than BGP-0%NTO having 2% MBF and zero Titania. Therefore, the specimen with 3% Titania illustrated 635 MPa of EM being the highest axial stiffness. The elevated elastic moduli of Titania-modified mortars might be associated with denser GP mortar and accelerated pace of polymerization as obtained with Titania inclusion to develop potential nucleation sites for associated supplementary products [19-21].

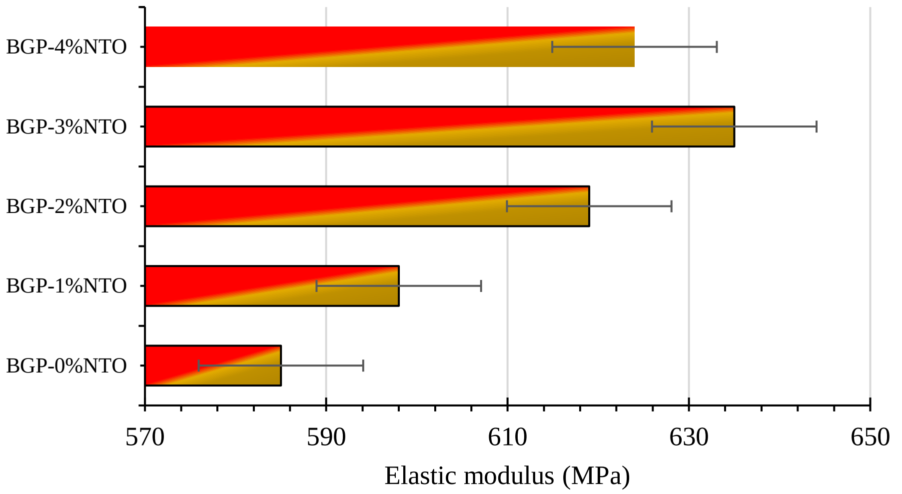

Fig 3. Elastic moduli of FRF-GP mortar for different dosages of Titania

In the following section, the relationship between the CS of GP mixes and compression elastic modulus is deliberated. Tests revealed a regularly rising linear relationship between the two variables. With the increase in CS, elastic modulus proportionally increased depicting that the increments of nano-Titania enhance the slope of the linear elastic region of the compressive stress-strain plot. Figure 4 depicts the established correlation between CS of GP mixes and associated elastic modulus.

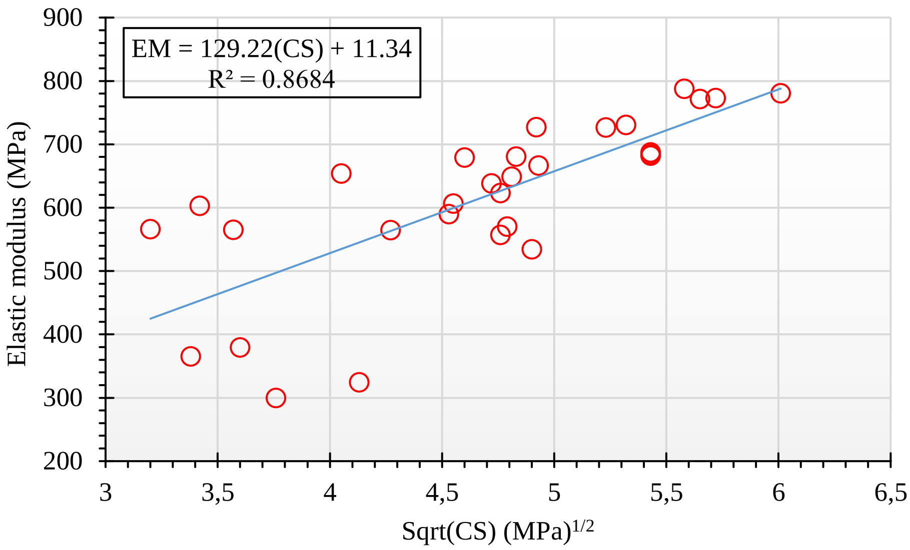

Fig 4. Relationship between CS and elastic modulus of GP mix

D. *Flexural Strength*

Figure 5 displays the efficacy of adding 2% MBF and varying amounts of Titania (0%, 1%, 2%, 3%, and 4%) to GP mortar on the FS of GP. The associated FS establishes the competency of any substance to withstand applied loading under flexure. The average FS outcome of the six samples from each GP mortar showed that before the final reduction in FS, it increased with adding the Titania up to the maximum limit of 3%. Whereas the inclusion of 4% Titania particles considerably reduced the FS, not lesser than that of the reference mortar. This reduction may be ascribed to the agglomeration of nano-materials and MBF and nanoparticles [23]. Nevertheless, the FS was larger than that of the reference mortar (BGP-0%NTO) due to the enhanced bending loads of these mortars as shown in Figure 5. This improvement in the FS of developed mortars might be associated with the associated enhanced microstructure by the inclusion of Titania particles, which eventually increased the pace of the polymerization for the GP mortar causing a denser GP mortar.

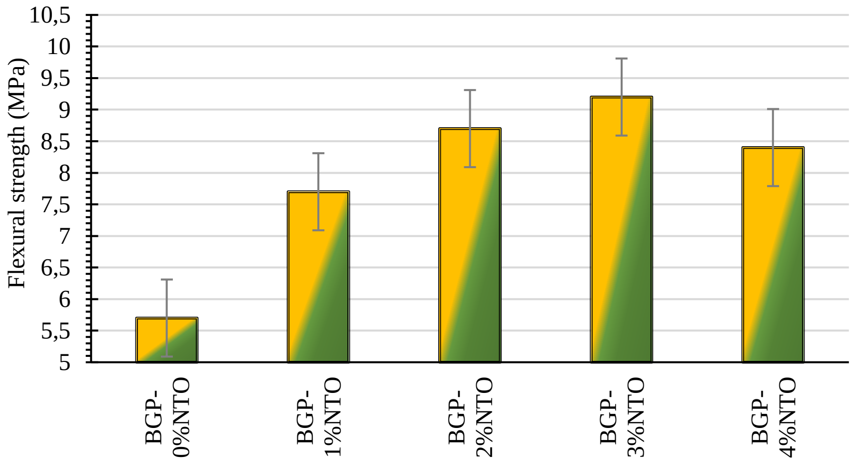

Fig 5. FS and bending loads of FRF-GP mortar for different dosages of Titania

The reductions in the FS of GP by increasing the Titania beyond 3% might be attributed to the agglomeration and accumulation of the nanoparticles. Similar findings were obtained with plain GP mortars comprising up to 3% Titania [22]. Also, the Titania amounts of 1% and 2% reduced the FS without MBF [22]. Nevertheless, the GP with 2% MBF enhanced the FS at all percentages of 1%, 2%, 3%, and 4% Titania in contrast to BGP-0%NTO. Employing 3% Titania illustrated the peak FS of GP mortars. Likewise, Titania modified GP mortar at the dosages of 1% and 2% of Titania, associated flexural capacities enhanced by

5.60% and 44.50%, respectively [12]. Still, the addition of Titania at the dosages of 1%, 2%, and 3% enhanced the FS by 35% 53%, and 61%, correspondingly, in the current study. Therefore, adding Titania along with the reinforcement of MBF can surely magnify the FS by employing only Titania. The FS of GP mortar with 1%, 2%, 3%, and 4% dosages of Titania, and 2% MBF were 135%, 153%, 161%, and 147% of the FS of control mortar having 2% MBF and with no Titania, correspondingly.

IV. CONCLUSION

The goal of the current experimental programme is to investigate the mechanical characteristics of the micro-basalt FRF-GP mortar with varying nano-Titania concentrations. The primary conclusions drawn from the current investigation are as follows:

1. The peak CS of basalt-FRF-GP mortars is achieved by employing 3% Titania which is 27% larger in contrast to the CS of the reference mortar without Titania. This might be ascribed to the potential of nanoparticles to minimize the cracks accompanied by the competency of the Titania to magnify the pace of the polymerization. The peak elastic modulus is obtained using 3% Titania along with 2% MBF being 8% higher than the control mortar.
2. The largest FS is achieved by employing 3% Titania being 61% higher than the control mortar. This enhancement in the FS of GP can be explained by the enhanced microstructure developed from the inclusion of Titania and improved polymerization reaction for the GP mortar developing a denser GP mortar. The peak toughness modulus is obtained using 3% Titania along with 2% MBF being 66% higher than the control mortar. This may be ascribed to the increased stiffness of the GP mortar by the addition of Titania and MBF.

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