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***Research Article***

# Fracture Toughness, Hardness, and Impact Strength of Basalt Fiber-Reinforced Engineered Cementitious Composites

Shahir Ahmad Safi[*1], Ali Raza[1] and Mujib Ul Rahman Rahmani[1]

[1]*Department of Civil Engineering, University of Engineering and Technology (UET), Taxila, 47050, Pakistan*

[*]*(safi.researcher@gmail.com)*

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***Abstract*** – The Engineered Cementitious Composites (ECC) mortars are the most suitable alternatives for cement in the concrete industry in developing sustainable and environmentally friendly construction. Therefore, for the practical applications of fiber-reinforced (FRF) ECC mortars, it is essential to increase the mechanical and microstructural behavior of FRF-ECC mortars utilizing micro-fibers and nano-particles. The present study has struggled to ameliorate the fracture and impact behavior of micro basalt-FRF fly ash-based ECC mortars by adding different amounts of nano-Titania. Four different dosages of Titania (varying between 1% and 4%) of the mortar are used to manufacture ECC mortars comprising 2 wt.% of micro-basalt fibers (MBF). For a comparative assessment, a control model with 2% MBF having no dosage of Titania is also manufactured. The outcomes of the current study displayed that the use of 3% Titania in micro basalt-FRF-ECC mortar improved the hardness, impact strength, and fracture toughness by 17.1%, 54.3%, and 25%, respectively. Consequently, the usage of Titania is operative in the enhancement of the mechanical and fracture behavior of FRF-ECC mortar. These bands appear larger and more pronounced in specimens containing additivesthis could be due to the high content of water within ECC network, which could affect the strength.

*Keywords – Engineered Cementitious Composites; Micro-Basalt Fibers; Nano-Titania; Hardness, Impact Strength.*

## I. INTRODUCTION

The cement manufacturing industry's substantial carbon emissions pose significant challenges to environmental sustainability. Engineered Cementitious Composites (ECC) offer a promising alternative to Portland cement for concrete construction due to their exceptional performance [1-5]. ECC mortar functions as an effective binding material in mortars that can be produced by activating aluminosilicate sources, such as fly ash, with an alkaline solution [6-12]. Over time, the development of ECC has demonstrated its ability to exhibit structural behavior comparable to, or even superior to, that of conventional concrete [13-15]. However, enhancing ECC's practical applications in construction requires substantial improvements in its behavior through advanced techniques.

Despite its advantages, ECC exhibits reduced early strength and brittle characteristics, which limit its suitability for applications demanding high flexural strength (FS) [16]. Therefore, innovative methods are crucial for enhancing the structural behavior of ECC mortars. The incorporation of nano-particles and micro-fibers has shown potential to significantly enhance the mechanical and microstructural performance of ECC mortars.

Recent studies indicate that ECC mortar reinforced with fibers outperforms fiberless ECC in mechanical behavior [17-25]. Micro-basalt fibers (MBF), known for their ability to limit micro-crack propagation and absorb energy during the pull-out process, have proven effective in enhancing ECC's mechanical properties [21]. When added to fly ash-based ECC mortar, MBF reduces dry shrinkage, increases compressive strength (CS), and extends setting time [26]. Research on micro-fiber inclusion in ECC has further confirmed that adding 10 wt.% micro-fibers improves CS by 37% [19]. However, increasing micro-fiber content to 15-30 wt.% yields no significant further improvement in CS. Thus, micro-fibers are a viable option for reinforcing ECC mortars, with a 40% increase in CS observed when 2 wt.% basalt fiber of the binder was incorporated into the mix [22]. These findings suggest that MBF effectively enhances ECC mortar's mechanical properties.

A comprehensive review of the literature reveals a gap in studies investigating the combined effects of MBF and Titania on the mechanical and microstructural properties of ECC mortars. This study aims to address this gap by examining the influence of various Titania dosages on basalt-fiber-reinforced (FRF) ECC mortars. ECC mortars were prepared by incorporating 2% MBF along with Titania at varying dosages (0%, 1%, 2%, 3%, and 4% wt.%). The study evaluates the effects of Titania on key mechanical properties, including CS, elastic modulus (EM), compressive strength-strain behavior, toughness modulus (TM), FS, flexural strength-strain behavior, impact strength (IS), fracture toughness (FT), and hardness (HN) of ECC mortars. The findings of this study are expected to guide structural designers in developing sustainable concrete construction materials.

## II. TESTING PROGRAM

### i. Materials

Nano-Titania (P25, 75% anatase, 25% rutile) with particle sizes between 1 and 30 nm is utilized in this research. Titania's primary composition is 99.68% Titania. Table 1 outlines the properties of Titania incorporated at varying percentages in the fabricated ECC mortar. The MBF employed in this study exhibits a tensile strength of 1800 MPa and an elastic modulus of 70 ECCa, with nominal dimensions of 2 mm in length and 7 μm in diameter.

Table 1. Features of Titania

| Property | Value | Property | Value |
|---|---|---|---|
| Specific gravity | 0.24 g/cm$^3$ | Ratio of anatase to rutile | 80: 20 |
| Median particle size | 20 nm | Shape | spherical |
| Content of Titania | 99.7% | LOI | < 0.01 |

In this study, Class F fly ash was used as the aluminosilicate precursor. The chemical properties of the fly ash are detailed in Table 2. A combination of sodium silicate and NaOH served as the dual activator for the preparation of ECC mortars. The NaOH was acquired as 98%-pure flakes, while sodium silicate was obtained in solution form. The composition of the sodium silicate solution included 30% SiO2, 12.5% Na2O, and 57.4% H2O.

Table 2. Composition of fly ash

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

Five ECC mixes incorporating varying percentages of Titania by the mass of fly ash were developed and evaluated for CS, FS, EM, FT, TM, and HN. An alkaline solution-to-fly ash ratio of 0.45 was maintained, while the sodium silicate-to-NaOH ratio was set at 2.5 for all ECC mixes [27]. To prepare the alkaline solution with a molarity of 12, NaOH pellets were dissolved in water and then mixed with sodium silicate solution, allowing the mixture to sit for 24 hours before producing the ECC mortars. Each ECC mix was reinforced with 2% MBF, and Titania was added in increments of 1%, 2%, 3%, and 4%, respectively.

### ii. Development and Testing of Specimens

A Hobart mixer is employed for the preparation of ECC mortars. During this process, fly ash and MBF are dry-mixed for 5 minutes at a low speed. Once the dry mixing of these two components is completed, an alkali solution with varying dosages of Titania is introduced, and the mixing is carried out at a high speed. This continues until a uniform ECC mortar is achieved. The freshly prepared mortars are then poured into molds and subjected to curing at 80°C for 24 hours. Following the initial curing, the specimens are demolded and further cured at room temperature for 28 days to enhance their mechanical properties.

The FT of ECC is evaluated using specimens measuring 70 mm x 20 mm x 20 mm. For each ECC group, 30 specimens are tested to determine FT. The average FT values for each group, based on five specimens, are analyzed in this study. Prior to testing, a crack with a depth-to-width ratio of 0.4 is induced in the specimens, which are then subjected to three-point bending tests at a deflection rate of 0.5 mm/min. The FT measurements are carried out following the procedure outlined in a previous study [28].

The HN of ECC is assessed using a Rockwell HN tester on the Rockwell H scale, as per ASTM D785 [29]. Six specimens from each ECC mix containing 0%, 1%, 2%, and 3% Titania are tested sequentially. The study discusses the average HN values for each group, calculated from five specimens. Before testing, the specimens are cleaned and polished to ensure precise results at room temperature.

To measure the IS, Zwick Charpy impact testing equipment with a Joule pendulum hammer is utilized. The specimens have a total length of 40 mm. The IS determination is conducted following the methodology detailed in an earlier study [30].

## III. RESULTS AND DISCUSSION

### i. Fracture Toughness

The FT of materials represents their capacity to resist the propagation of crack widths. Figure 1 illustrates the FT values for five basalt-FRF-ECC mixtures containing 0%, 1%, 2%, 3%, and 4% Titania. It is evident that ECC mortars with Titania exhibit higher FT values compared to BECC-0%NTO. This improvement in FT can be attributed to the incorporation of MBF, which enhances the matrix stiffness. The MBF bridging mechanism within ECC mortar further contributes to the increased FT, as the fibers effectively transfer internal stresses among the mortar components, thereby enhancing resistance to crack initiation and expansion.

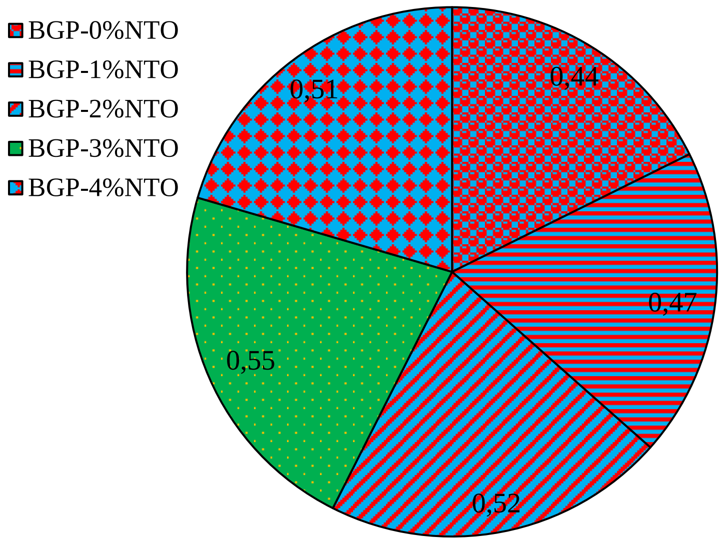


Figure 1. FT of FRF-ECC mortar for different dosages of Titania (MPa.m$^{1/2}$)

The FT of mortars consistently improved with an increase in Titania dosage from 1% to 3%, reaching the highest FT value of 0.55 MPa.m1/2 at 3% Titania. However, all ECC mortars containing Titania demonstrated higher FT than those without Titania, highlighting its role in enhancing the toughness of ECC mortars. The FT of the ECC specimen BECC-1%NTO was 6.8% higher than that of the control specimen BECC-0%NTO. Similarly, the FT of the ECC specimen BECC-2%NTO showed an 18.2% improvement compared to the control specimen BECC-0%NTO. When the Titania dosage was increased to 4%, the FT decreased relative to the dosages of 1%, 2%, and 3%. The specimen BECC-3%NTO exhibited a 25% increase in FT compared to the control specimen BECC-0%NTO, while BECC-4%NTO showed a 15.9% improvement over the control. The enhancement in FT of ECC mortars due to Titania inclusion can be attributed to the ability of Titania nano-particles to strengthen the interfacial zone between the ECC matrix and MBF. This improvement enhances the bridging behavior of MBF within the ECC mortar. The presence of nano-particles enhances the bond among ECC mortar components and fibers, resulting in a denser, tougher matrix capable of resisting cracks [31]. Consequently, the incorporation of nano-particles accelerates the polymerization process and refines the microstructure of ECC mortar by strengthening the bond between its components and MBF.

### ii. Hardness

The HN of ECC mortar reflects its ability to endure localized plastic deformation. Figure 2 illustrates the effect of incorporating 0%, 1%, 2%, 3%, and 4% Titania on the HN of basalt FRF-ECC mortars. The findings demonstrated that the addition of Titania enhanced the HN of ECC mortars, reaching its highest value at 3% Titania content. Compared to the control sample BECC-0%NTO, BECC-1%NTO exhibited a 4.9% improvement in HN, while BECC-2%NTO showed a 13.4% enhancement. Similarly, BECC-3%NTO achieved a 17.1% increase in HN relative to the control, whereas BECC-4%NTO recorded an 11% improvement in HN when compared to BECC-0%NTO. The observed improvement in HN is likely attributable to the superior strength of Titania particles, which are evenly distributed throughout the ECC mortar, creating an extensive interfacial area between the ECC matrix and the nanoparticles, thus facilitating internal strength transfer [32]. The nanoparticles effectively disperse within the ECC mortar and fill voids within its chains, enhancing the material's resistance to deformation and crack propagation. Previous research on ECC incorporating nanoparticles revealed that mortars without nanoparticles or fibers exhibited an HN of 80 HRH [33]. Consequently, the higher HN values observed in this study (> 80 HRH) may also result from the inclusion of MBF, underscoring the beneficial role of basalt fibers in ECC mortar.

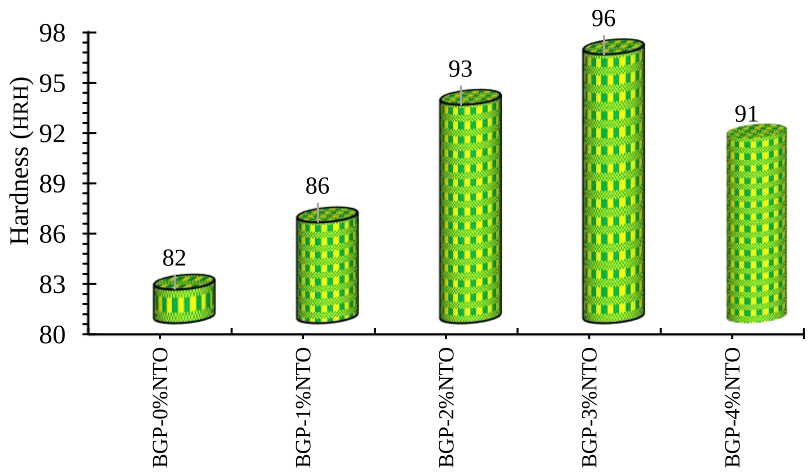


Figure 2. HN values of FRF-ECC mortar for different dosages of Titania

### iii. Impact Strength

Figure 3 illustrates the IS of basalt-FRF-ECC with varying Titania dosages. The findings indicate that incorporating Titania particles enhances the IS of the ECC mortar. The impact energy of the ECC matrix improves up to a Titania content of 3%, beyond which it decreases but remains higher than the specimen without Titania. The highest IS for the basalt-FRF-ECC mortar is achieved with 3% Titania. The IS of BECC-1%NTO exceeds that of BECC-0%NTO without Titania, showing a 17.3% increase. Similarly, the IS of BECC-2%NTO is 30.9% higher than that of BECC-0%NTO. For BECC-3%NTO, the IS is 54.3% greater than BECC-0%NTO without Titania, while BECC-4%NTO shows a 9.9% improvement over BECC-0%NTO. The reduction in IS for higher dosages of Titania may result from nanoparticle agglomeration, which acts as a stress concentration site, initiating cracks. This enhancement is likely due to improved bonding between MBF and ECC components, resulting in a more robust matrix capable of resisting crack propagation [31].

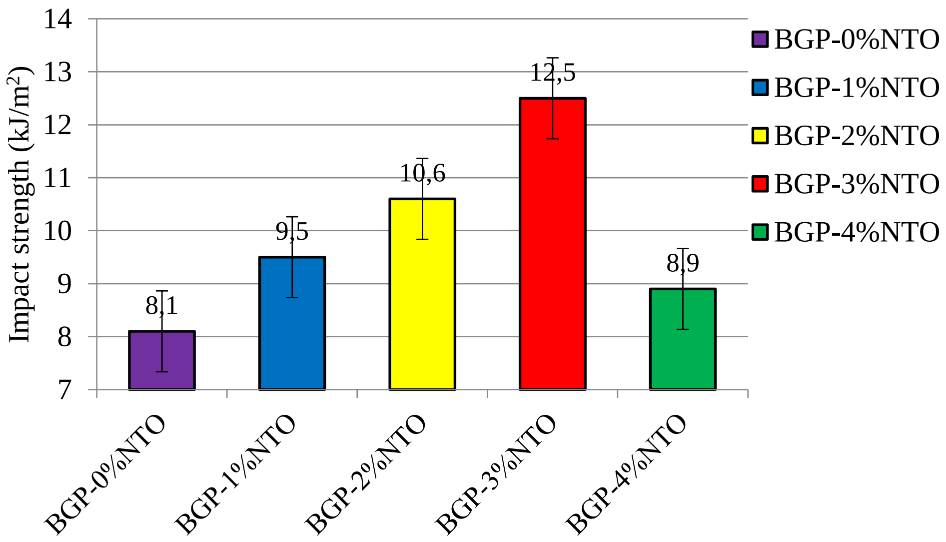


Figure 3. IS values of FRF-ECC mortar for different dosages of Titania

An ECC matrix exhibits optimal performance when the load-transfer mechanisms between nano-particles function effectively. Since the behavior of Titania nano-particles relies on the transfer of load from the ECC mortar to the Titania, the interfacial toughness between the matrix and Titania plays a crucial role. The bridging capability of Titania and MBF enhances the impact energy of basalt FRF-ECC mortar with varying Titania content. Additionally, incorporating MBF improves the load-transfer process and interface by strengthening the bond and facilitating a bridging effect among the mortar's components. Consequently, a more robust interfacial area enhances load transfer and improves IS.

## IV. CONCLUSION

The experimental study aimed to assess the effect and fracture characteristics of micro-basalt FRF-ECC mortar with varying proportions of nano-Titania. The main findings of this investigation are as follows:

1. The flexural toughness (FT) of the mortars increases with the inclusion of Titania, reaching its maximum value at 3% Titania, which is 25% higher than that of the control mortar. This improvement in FT is attributed to the filling effect of Titania and the formation of micro-basalt fibers (MBF), which facilitate crack bridging, enhance internal strength transfer, and provide significant crack resistance.
2. The incorporation of Titania also boosts the impact strength (IS) of the ECC mortar, with a peak observed at 3% Titania, showing a 54.3% increase compared to the control mortar. Similarly, the highest hardness number (HN) is achieved with 3% Titania, which is 17.1% greater than the control. This enhancement can be attributed to the role of Titania particles in improving the bonding between the MBF and other ECC components, leading to a more compact matrix that effectively prevents crack propagation. Consequently, the mechanical and fracture properties of the Engineered Cementitious Composites mortar can be significantly enhanced with the addition of micro MBF and nano-Titania.

## CONFLICTS OF INTEREST

The authors have no conflicts of interest.

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