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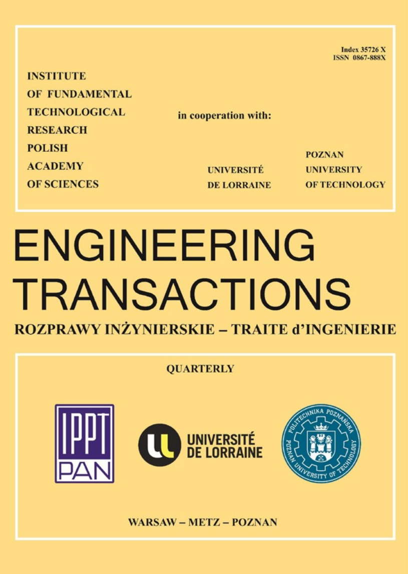
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Study on Mechanical, Physical and Thermal Properties of Oil Palm Mesocarp Fiber Composite with Eco-Friendly Sodium Bicarbonate Treatment of Fiber

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Abstract

This article studied the effect of variation of sodium bicarbonate ($NaHCO_3$) concentration fiber treatment on the mechanical, physical, and thermal properties of oil palm mesocarp fiber (OPMF) composite. The components of the OPMF composite are OPMF and polyester resin. OPMF composite was fabricated by hand lay-up, followed by the compression method. Before composite fabrication, the treatment of OPMF was conducted by $NaHCO_3$ concentration variation, including 8 wt%, 10 wt%, and 12 wt%. Mechanical testing (tensile and flexural), physical testing (water absorption and thickness swelling), and thermal testing were performed. Scanning electron microscopy (SEM) verified the composite's surface tensile fracture. The results show that the mechanical properties of the OPMF composite have improved after $NaHCO_3$ treatment. 12 wt% treatment produces the best mechanical properties. Then, the physical and thermal properties of the composite with 12 wt% treatment were found to be the best, with the lowest swelling and thermal stability, respectively.

Keywords: Oil palm mesocarp fiber, Composite, Sodium bicarbonate, Eco-friendly treatment.

1. INTRODUCTION

The increasing global demand for sustainable and eco-friendly materials has led researchers to explore natural fiber composites as an alternative to synthetic fiber-reinforced composites. Oil palm mesocarp fiber (OPMF) is one of the natural fibers that has drawn interest due to its availability and renewable nature for use in composite materials. A vital agricultural product for palm manufacturing, oil palm (Elaeis guineensis) is extensively grown in tropical countries, especially Indonesia and Malaysia. The mesocarp fiber, a by-product of palm oil production, has historically been underutilized, producing its compounding into composites an attractive prospect for waste reduction and value addition [1].

Natural fiber composites have obtained attention in industries such as automotive, construction, and packaging due to their lightweight nature, biodegradability, and recyclability [2-6]. However, natural fibers, including OPMF, exhibit limitations such as high moisture absorption, poor interfacial adhesion with polymer matrices, and susceptibility to degradation [7, 8]. To overcome these drawbacks, researchers have explored various fiber treatment methods, including chemical and eco-friendly treatments, to enhance the resulting composites' mechanical, physical, and thermal properties [9, 10].

Alkali treatment, silane coupling, and acetylation are examples of conventional chemical treatments that have been widely utilized to enhance fiber-matrix bonding and improve composite characteristics [11-13]. However, these treatments often involve hazardous chemicals that pose environmental and health risks [14]. Non-toxic fiber treatment methods, such as enzymatic [15], steam explosion [16], sodium bicarbonate [17, 18], and plasma [19, 20], have become feasible alternatives as a sustainable substitute. These methods aim to modify fiber surface characteristics without compromising environmental safety. For instance, steam explosion can repair fiber adhesion with the matrix in composite [16, 21]. Likewise, sodium bicarbonate treatment of natural fiber as reinforcement composite with different immersion time and concentration can improve adhesion of fiber-matrix [14, 17, 18].

Several studies have used sodium bicarbonate to surface treat natural fibers as a composite reinforcement to enhance performance. With variation of sodium bicarbonate concentration (5 wt% and 10 wt%), the 10 wt% sodium bicarbonate concentration enhanced the tensile strength of jute fiber, improved the interfacial shear strength and flexural properties of jute/epoxy composites [22], and increased tensile strength and modulus of flax fiber composite [14]. Then, at room temperature, 10% $NaHCO_3$ concentration with different immersion times of coir fibers for 24, 96, and 168 h. When a mildly alkaline solution was used, the mechanical strength of the coir fiber composites was not influenced. However, the tensile and flexural modulus rose as the treatment duration was extended to 96 or 168 hours [23]. Furthermore, variation of $NaHCO_3$ treatment time (24, 120, and 240 hours) of phoenix sp. fiber as reinforcement of composite, 120 h treated fiber has the highest mechanical properties (i.e., tensile, flexural, and impact strength) than other treatment times [24].

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Sodium bicarbonate treatment has been used previously by authors [25]. Fiber treatment's impact on coir fiber-epoxy matrix adhesion was evaluated with sodium bicarbonate concentration variation. The experimental results displayed that changes in the mechanical behavior and chemical composition of the fibers occur when they are treated with 8%, 10%, and 12% in weight solution of sodium bicarbonate for 24 and 120 hours.

This study investigates the mechanical, physical, and thermal properties of OPMF composites treated with the eco-friendly sodium bicarbonate, highlighting their potential for sustainable material applications. Treatment with sodium bicarbonate ($NaHCO_3$) was adjusted according to concentration (8 wt%, 10 wt%, and 12 wt%) and compared with untreated fiber (0%).

2. MATERIALS AND METHODOLOGY

2.1. Materials and Fabrication of Composite

The oil palm mesocarp fiber (OPMF) used in this research was gained from the fruit of the oil palm, which is the residual milling of palm fruit oil during the production of crude palm oil. Sodium bicarbonate ($NaHCO_3$) treated the fiber before composing with the matrix. Unsaturated polyester was used as a matrix. Fig. 1 depicts the generation of OPMF, which arises as solid waste from the utilization of oil palm trees

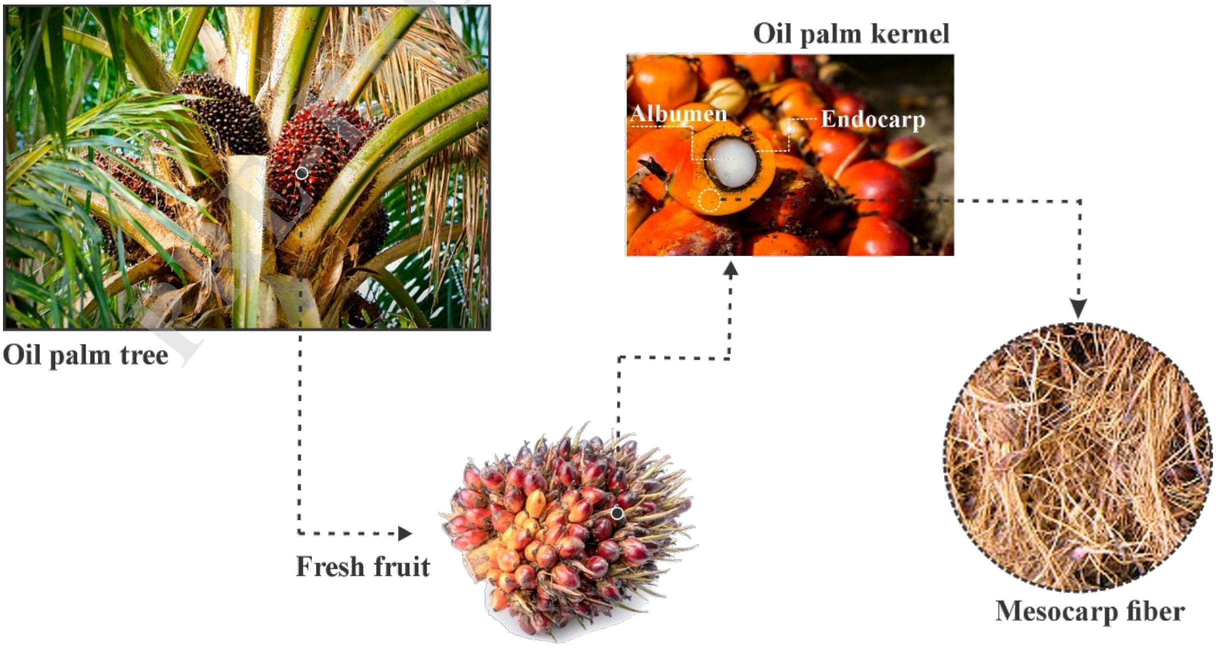

Fig. 1. OPMF is a solid bio-waste from oil palm trees and their by-products

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This investigation used untreated and treated $NaHCO_3$ OPMF to reinforce the composite. Untreated fiber is marked as 0%. For treated fiber during 120 hours at room temperature, fibers were immersed in several concentrations of $NaHCO_3$ solution (8 wt%, 10 wt%, and 12 wt%). Following soaking, the fibers were cleaned with distilled water, allowed to dry at room temperature for 24 hours, and then dried in an oven for 1 hour at 110 °C [18].

OPMF composites were fabricated with a fiber volume fraction of 30% and 70% polyester resin. The mixing of unsaturated polyester and a catalyst was poured into the mold along with the OPMF. Compression molding using a four-ton manual hydraulic press machine follows the manual lay-up method shown in Fig. 2.

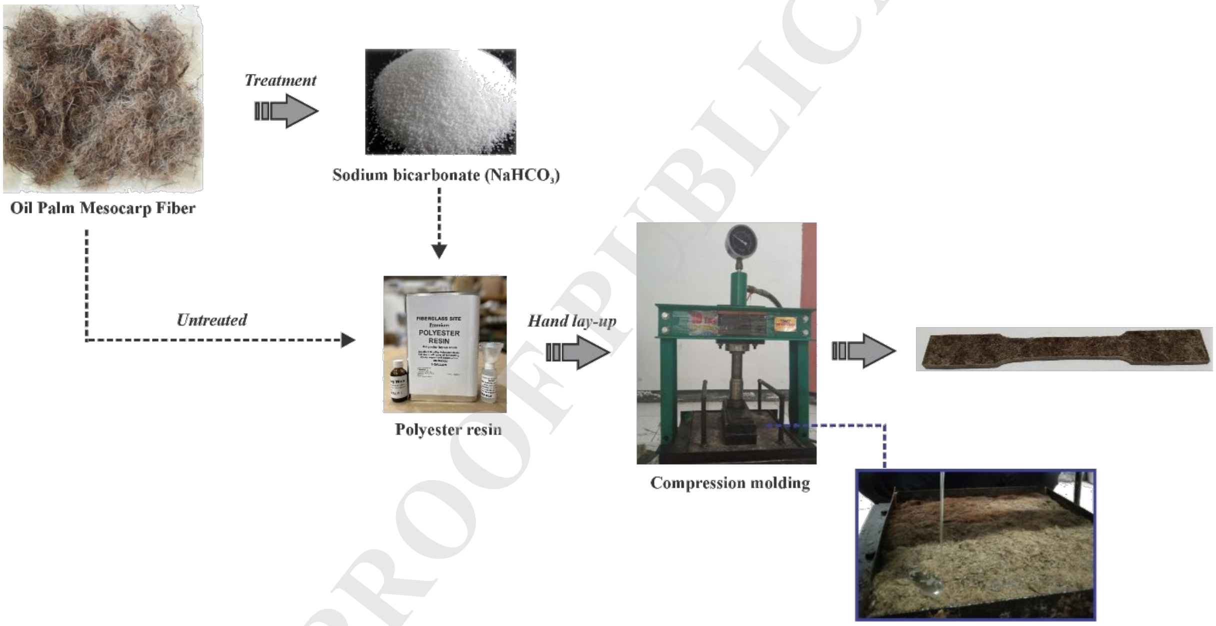

Fig. 2. Fabrication of OPMF composite

2.2. Methodology

The tensile testing of the OPMF composite was conducted using a Universal Testing Machine (UTM, model TN–MD, serial no. 0014003.1/3.2/3.3) with a capacity of 200 kN, following the ASTM C638-02 standard. Then, the flexural testing with a three-point bend uses a Universal Testing Machine. It was conducted according to ASTM D 790-02 standard, typically 80 mm × 20 mm × 5 mm. A total of 10 samples were prepared for each variation, and each experiment was conducted 10 times to ensure measurement accuracy and repeatability. Untreated and all treated fiber variations were tested for each $NaHCO_3$ concentration to determine the average values of tensile strength, tensile modulus, flexural

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strength, and flexural modulus. The sodium bicarbonate ($NaHCO_3$) employed in this study was supplied by Merck, Germany, with an analytical grade purity of ≥99.7%.

Water absorption and thickness swelling are the physical characteristics of the composite that were tested in this work. Based on ASTM D 570-98 standard test procedure, the water absorption test was employed with a sample dimension of 25.4 mm wide by 76.2 mm long. The water absorption (%W) can be calculated by Eq. 1 [26].

$$\%W = \frac{W_t - W_o}{Wo} \tag{1}$$

Where W_t is the wet weight after immersion, and W_o is the initial weight. The water absorption sample and the thickness swelling sample are identical. All samples' thicknesses were measured during the water absorption test to determine the thickness swelling. The thickness swelling (ts) can be computed using the subsequent Eq. 2 [26].

$$\%ts = \frac{h_t - h_o}{ho} \tag{2}$$

Where h_t is the sample thickness after immersion, and h_o is the initial thickness. The thermal stability of OPMF composite samples was tested using TGA (TG/DTA Hitachi STA7300). The thermogravimetry (TG) curves were recorded from 30 to 600 ºC at a heating rate of 10 ºC/min in a nitrogen environment. Scanning electron microscopy (SEM) was used to analyze the surface fracture of the OPMF composite sample after tensile testing. The SEM–JEOL JSM 6510 LA type was used to capture images.

3. RESULTS AND DISCUSSION

The mechanical properties of composites reinforced with oil palm mesocarp fiber (OPMF) consist of tensile strength, tensile modulus, flexural strength, and flexural modulus. Fig.3 and Fig. 4 illustrate the correlation between $NaHCO_3$ treatment and tensile strength and tensile modulus, and NaHCO3 treatment and flexural strength and flexural modulus of oil palm mesocarp fiber composite. Fig.3 shows the effect of $NaHCO_3$ treatment on tensile strength and tensile modulus of oil palm mesocarp fiber composite.

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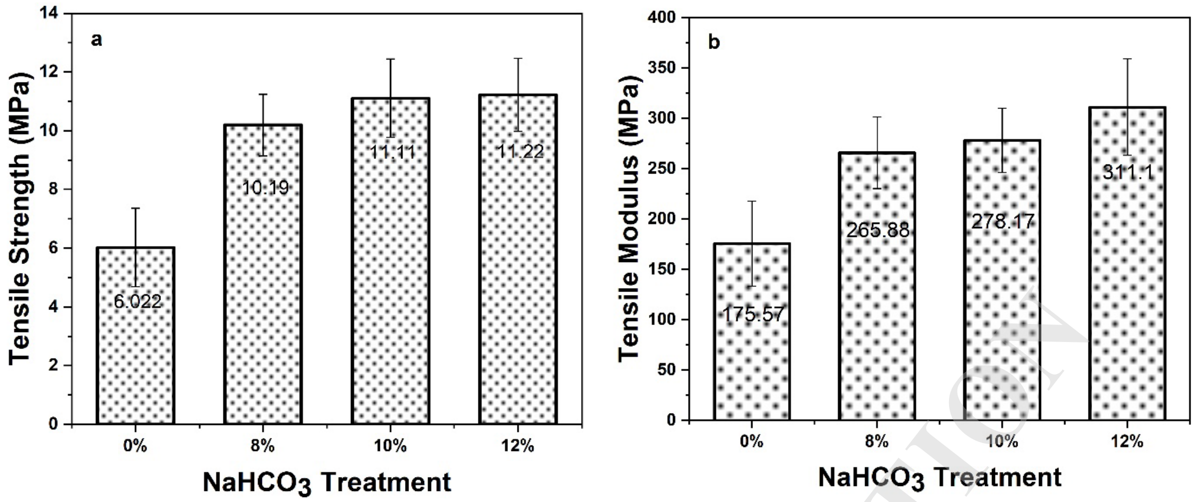

Fig. 3. Correlation between $NaHCO_3$ concentration treatment; a) tensile strength, b) tensile modulus

The different compositions of $NaHCO_3$ treatment (0%, 8%, 10%, 12%) affect the tensile strength and tensile modulus of oil palm mesocarp fiber composite. Tensile strength (TS) increases as $NaHCO_3$ concentration increases. The tensile strength is the lowest at the untreated fiber (0%). TS peaks at around 10% $NaHCO_3$ and remains slightly stable at 12%. The increase in TS of OPMF composite is caused by the removal of impurities and surface modification, leading to better interfacial bonding between fiber and matrix [14]. The enhancement of the crystalline structure of the fiber may also cause it. Then, tensile modulus exhibits a steady increase with increasing $NaHCO_3$ concentration. The highest TM is observed at 12% $NaHCO_3$ treatment. A consistent increase in TM presents increased stiffness with $NaHCO_3$ treatment. This indicates that the composite is more rigid and less deformable under tensile load, possibly due to enhanced crystallinity or better fiber orientation. It may also be better to transfer the load in the composite. The strengthening mechanism refers to the increase in the degree of crystallinity of cellulose due to the removal of amorphous components such as lignin and hemicellulose during sodium bicarbonate treatment [27]. This partial removal allows cellulose chains to rearrange more closely and form stronger intermolecular hydrogen bonds, resulting in a denser and more ordered crystalline region.

The orientation and distribution of fibers play a crucial role in determining the mechanical properties of composites. Fibers aligned parallel to the loading direction generally exhibit higher tensile and flexural strengths due to more efficient stress transfer between the matrix and the fibers. In contrast, chaotic-oriented fibers provide more isotropic behavior, allowing the load to be distributed in multiple

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directions, although the maximum strength is typically lower than that of aligned fibers [28]. A uniform distribution of fibers within the matrix also helps prevent localized stress concentrations and porosity, which can act as initiation points for material failure [29, 30]. Furthermore, the interaction between fiber orientation and interfacial adhesion significantly influences the effectiveness of load transfer, stronger interfacial bonding enhances the overall contribution of the fibers to the composite's mechanical performance [31].

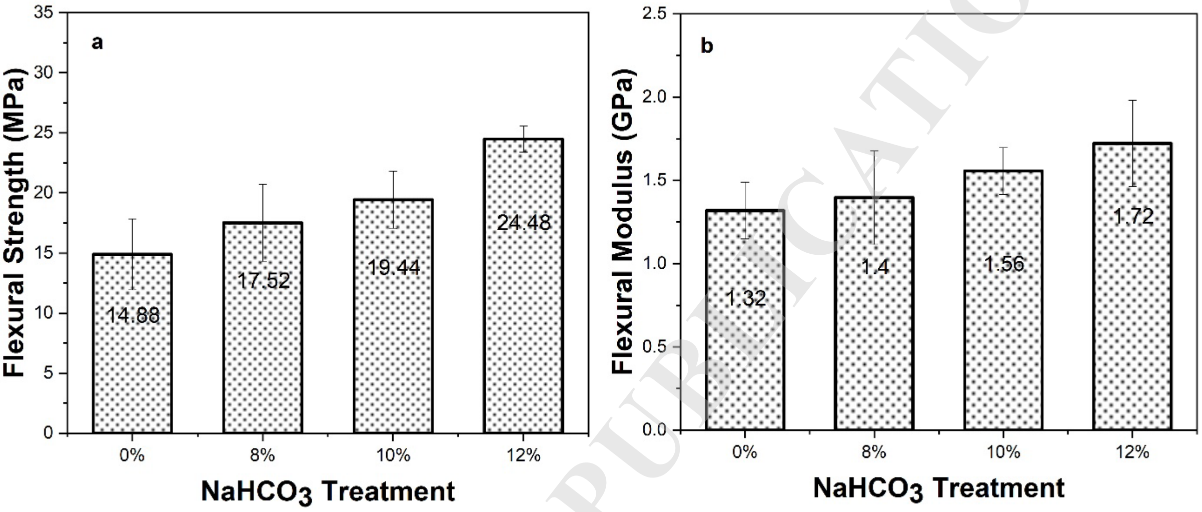

Fig. 4. Correlation between $NaHCO_3$ concentration treatment; a) flexural strength, b) flexural modulus

Fig. 4 depicts the correlation of $NaHCO_3$ treatment with flexural strength and flexural modulus. FS shows a positive correlation with $NaHCO_3$ treatment. The highest FS is recorded at 12% $NaHCO_3$ treatment, indicating significant enhancement. At the same time, the lowest FS is untreated fiber (0%). The highest FS of 12% $NaHCO_3$ treatment is possibly caused by modifying the chemical composition of the fiber, leading to stronger intermolecular bonds and removing impurities in the fiber, making the material denser and enhancing good fiber-matrix adhesion [17]. Furthermore, FM increases with increasing $NaHCO_3$ treatment, but the change is less dramatic than FS. The highest FM occurs in 12% $NaHCO_3$ treatment, about 1.72 GPa. The increase in FM indicates that the composite becomes stiffer with more $NaHCO_3$. This may be due to improved crystallinity, which enhances stiffness.

Fig. 5 shows the water absorption of the OPMF composite with immersion time. Water absorption increases rapidly in the first 48 hours and gradually levels off. All treated samples depict lower water

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absorption than the untreated (0%) sample. The untreated (0%) sample exhibits the highest water absorption, indicating higher hydrophilicity [26]. The samples treated with 8%, 10%, and 12% $NaHCO_3$ solution show reduced water absorption, with the highest concentration (12%) leading to the lowest absorption. This suggests that higher sodium treatment reduces water uptake, likely due to chemical modifications that improve hydrophobicity [32]. The improvement in tensile and flexural strength of the oil palm mesocarp fiber composites is supported by previous findings [18], which show that the contact angle between the fiber and matrix decreases with increasing sodium bicarbonate concentration. This reduction in contact angle occurs because the fiber surface becomes cleaner and micropores are formed after $NaHCO_3$ treatment, allowing the matrix to penetrate the fibers more easily. This condition enhances the interfacial bonding between the fibers and the matrix, leading to more efficient stress transfer. A lower contact angle indicates higher adhesion capability, which reflects improved wettability and contributes positively to the overall mechanical performance of the composite.

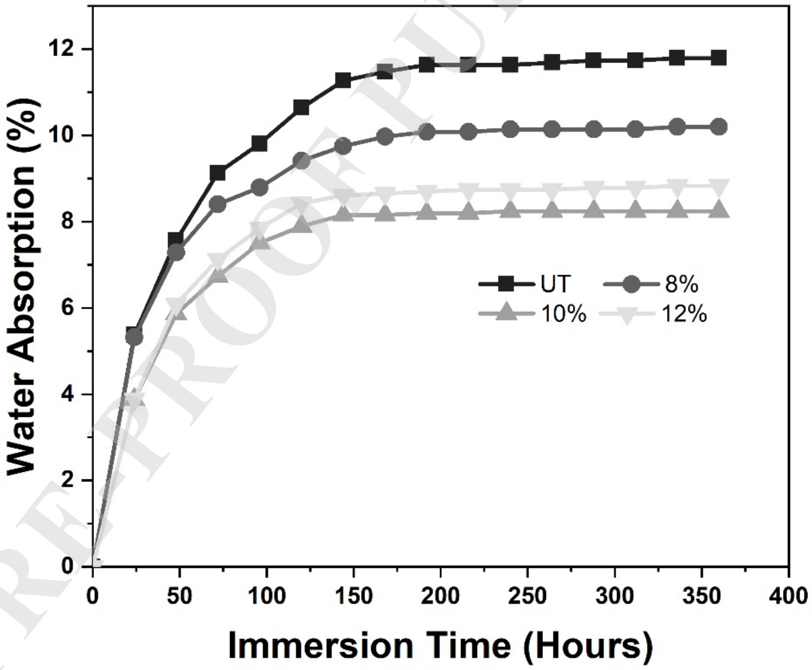

Fig. 5. Correlation between immersion time and water absorption on OPMF composite with variation of $NaHCO_3$ concentration treatment

Fig. 6 presents the relation between thickness swelling and immersion time of the OPMF composite with variation of $NaHCO_3$ concentration. All samples experience a rapid increase in thickness swelling within the first 48 hours. The untreated (0%) composite swells the most compared to the treated samples

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(8%, 10%, and 12% $NaHCO_3$). Then, in the 48-144 hours range, the swelling rate slows down for all samples [26]. The untreated (0%) sample shows the highest swelling percentage, around 4.15%. The treated samples (8%, 10%, and 12% $NaHCO_3$) stabilize at lower swelling values than the untreated sample. After 144 hours, swelling reaches a plateau, indicating the equilibrium in moisture absorption. The 8% sample swells less than the untreated (0%) sample but remains higher than the 10% and 12% treatments. 10% and 12% samples are the least swollen, showing better moisture resistance. Increasing $NaHCO_3$ treatment percentage of the composite reduces thickness swelling, implying better water resistance.

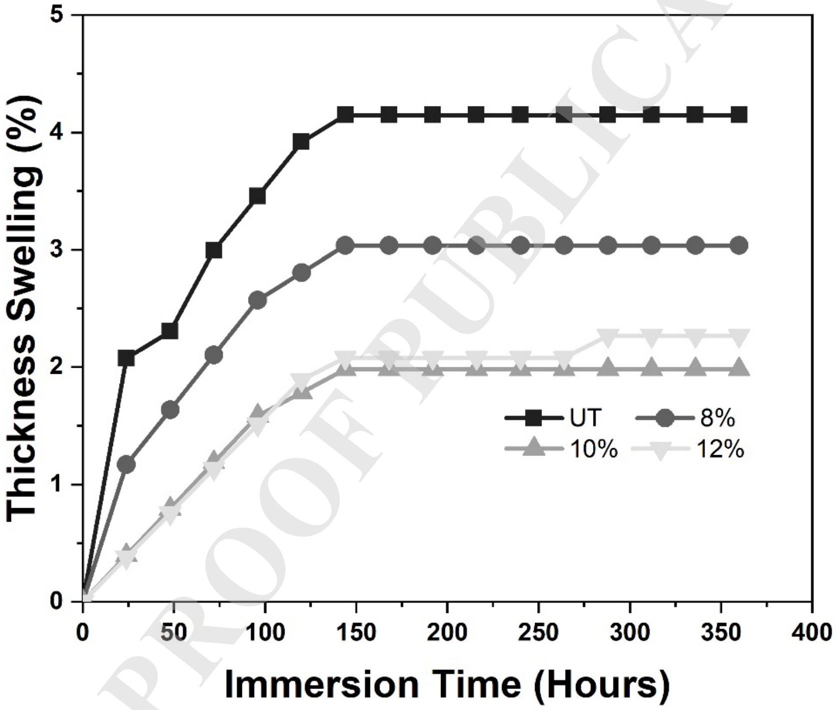

Fig. 6. Correlation between immersion time and thickness swelling on OPMF composite with variation of $NaHCO_3$ concentration treatment

The relation between water absorption and thickness swelling of the OPMF composites is depicted in Fig. 7. Following linear fitting, the chart's R-squared value ($R^2 = 0.99$), which indicates a close correlation between water absorption and thickness swelling, is displayed. This correlation has been investigated by Renreng et al. [26] for pressed coir fiber/epoxy composite using NaOH and fiber microwave treatment. The relationship between thickness swelling and water absorption can be seen in Fig.7.

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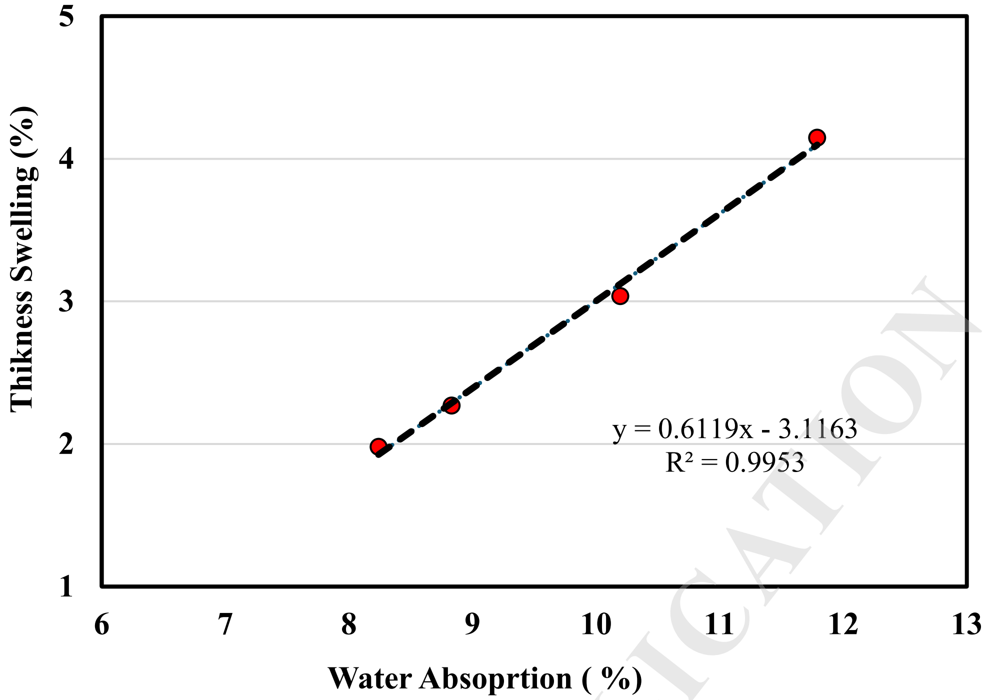

Fig. 7. Correlation between immersion time and water absorption on OPMF com-posite with variation of $NaHCO_3$ concentration treatment

Fig. 8 displays the thermogravimetric study of the OPMF composite and the relationship between temperature (°C) and weight loss (%). Figure 6 shows that the initial weight losses seemed lower than 150ºC caused by the dehydration or evaporation of moisture [3] in OPMF composites. Then, weight loss is moderate up to 250°C for all $NaHCO_3$ treatments. The primary decomposition of the composite is then represented by a notable weight loss between around 250°C and 400°C. The rate of weight loss decreases after 400°C, reaching thermal stability and decomposition completion. The different percentages of $NaHCO_3$ solution affect the thermal degradation of the composite. The untreated sample exhibits a specific deterioration pattern, while the thermal degradation behavior of 8%, 10%, and 12% $NaHCO_3$ varies significantly, with variations in residual weight at higher temperatures. The 12% $NaHCO_3$ sample maintains slightly more mass after decomposition, indicating enhanced thermal stability.

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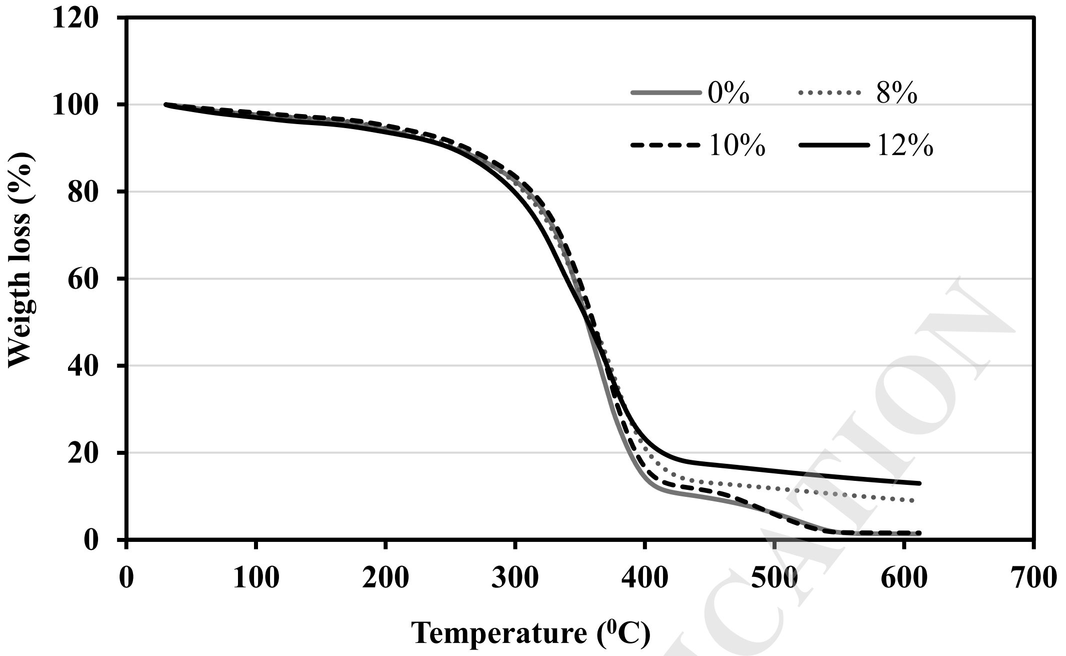

Fig. 8. Weight loss of OPMF composite as a function of temperature

Fig. 9 displays SEM images of the OPMF composite after tensile testing. The images compare untreated (0%) and $NaHCO_3$-treated fibers at various concentrations (8%, 10%, and 12%) to study their impact on fiber-matrix adhesion. In Fig. 9 (a), Poor fiber-matrix bonding is perceived with significant fiber pull-out and breakage. The weak adhesion between fibers and the matrix indicates ineffective load transfer, leading to premature failure. Then, Fig. 9 (b) shows a combination of poor and good fiber-matrix bonding; some fibers appear well bonded, but fiber pull-out and voids are still visible.

Furthermore, reduced fiber pull-out demonstrates strong fiber-matrix bonding (Fig. 9 (c)). Improved adhesion of fiber and matrix indicates chemical compatibility between fiber and matrix. Fiber breakage rather than pull-out is more dominant, indicating stronger interfacial bonding. Finally, Fig. 9(d) shows strong fiber-matrix bonding with minimal fiber pull-out. Less pull-out rather than fiber breakage, indicating that the fibers are well embedded in the matrix. More fiber breakage than pull out, implying the fibers are well embedded in the matrix [26]. 12% $NaHCO_3$ treatment significantly enhances adhesion, improving the mechanical integrity of the composite. This is in line with the tensile test results in Fig.3.

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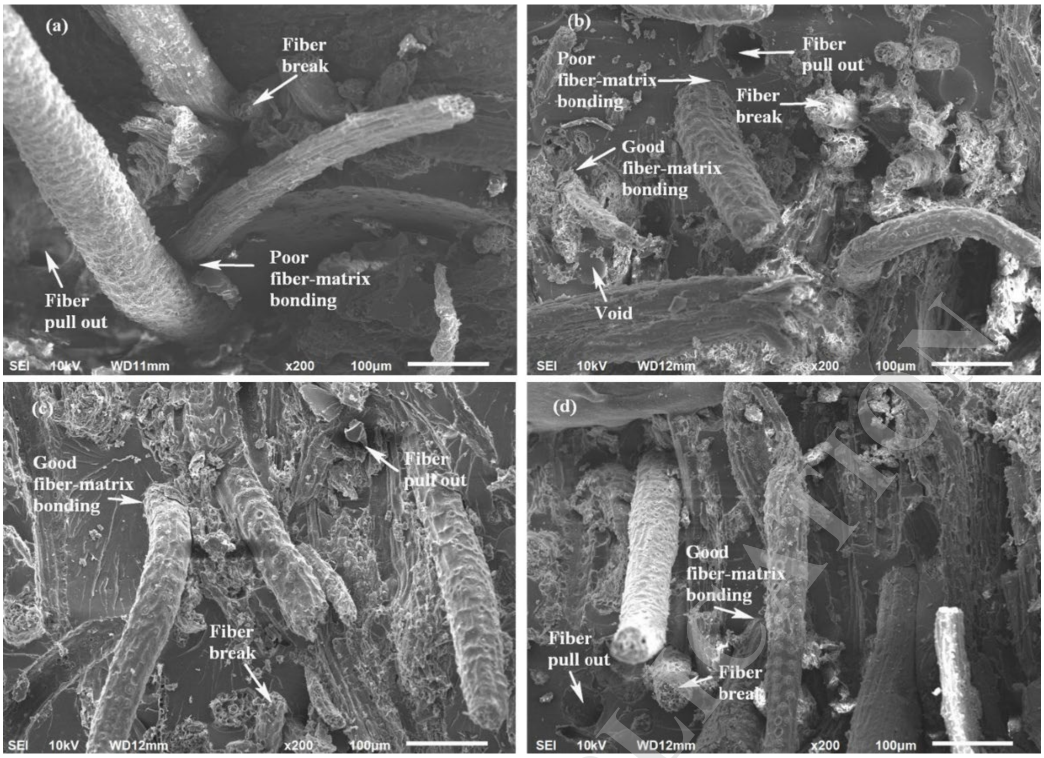

Fig. 9. Fracture tensile SEM images of OPMF composite with (a) Untreated fiber (0%) and $NaHCO_3$ treated (b) 8% (c) 10% (d) 12%.

Sodium bicarbonate functions as a mild alkaline medium, capable of partially eliminating non-cellulosic substances such as lignin, hemicellulose, and surface waxes, resulting in a cleaner and rougher fiber surface [18, 22]. This surface modification improves the interfacial bonding between the fibers and the polymer matrix, facilitating a more effective transfer of stress under applied loads. In addition, the removal of amorphous components enhances the crystallinity of the cellulose microfibrils, thereby improving the stiffness and mechanical strength of the fibers. During composite fabrication, this treatment also enhances fiber wettability and matrix infiltration, effectively minimizing interfacial voids and local stress concentrations.

4. CONCLUSION

This study's mechanical properties of OPMF composites include tensile strength, tensile modulus, flexural strength, and flexural modulus. The $NaHCO_3$ fiber treatment influences these mechanical properties. The results show that the 12% $NaHCO_3$ treatment produces the best mechanical performance compared to other treatments and without treatment. This is in line with the results of SEM analysis that the 12% treatment shows better fiber-matrix bonds, potentially optimizing the mechanical performance

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of OPMF composites. Then, the 12% treatment showed the best performance with the least swelling (physical properties), followed by 10%, 8%, and finally, the untreated fiber. This means that higher treatment concentrations increase dimensional stability in wet environments. Furthermore, the 12% $NaHCO_3$ sample retains slightly more mass after decomposition, implying increased thermal stability. These results provide potential applications for OPMF as a composite reinforcement and environmentally friendly sodium bicarbonate treatment.

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