International Journal of GEOMATE, Dec., 2023 Vol.25, Issue 112, pp.75-82
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2023.112.4211
Geotechnique, Construction Materials and Environment

CHEMICALLY STABILIZED FIBER OF OIL PALM EMPTY FRUIT BUNCH FOR SOIL STABILIZATION

*Yulian Firmana Arifin[1, 2, 3], Adriani[2], Muhammad Arfiandoyo[2], Nada Salsabila[3], Muhammad Hafizhir Ridha[3]

[1]Wetland-Based Material Research Center, University of Lambung Mangkurat, Banjarbaru, Indonesia
[2]Civil Engineering Study Program, University of Lambung Mangkurat, Banjarbaru, Indonesia
[3]Civil Engineering Master Program, University of Lambung Mangkurat, Banjarbaru, Indonesia

*Corresponding Author, Received: 03 Nov. 2023, Revised: 22 Nov. 2023, Accepted: 30 Nov. 2023

ABSTRACT: The exploration of oil palm empty fruit bunch (OPEFB) fiber as a construction material, especially in geotextile applications, is a growing area of interest. However, OPEFB fibers degrade rapidly, particularly in soil conditions, due to their natural composition. This study investigates the application of an alkaline solution, sodium hydroxide (NaOH), for enhancing the fiber strength and durability. OPEFB fibers, sourced from a palm oil mill in the Tanah Bumbu Regency, were treated via immersion in a 1N NaOH solution for 90 min. Subsequently, these treated fibers were embedded in soft soil and cured for 1, 7, 14, and 28 d under both open and closed conditions (that is, covered with plastic wrap). Tensile strength was assessed using specialized equipment designed for this purpose. Additionally, the fibers were blended with soil at a percentage of 7% based on dry weight, and compacted with 10% water content and a dry volume weight of 16 kN/m^3. These samples were then tested for compressive strength, revealing a substantial improvement in the average tensile strength of fibers treated with NaOH at 288.22 MPa, which is 2.77 times greater than untreated fibers. Furthermore, the treated fibers exhibited enhanced durability, with tensile strength ranging between 160.2–179.58 Mpa and 184.11–222.2 MPa under closed and open conditions, respectively. Additionally, the compressive strength of the soil with treated fibers exceeded that of the soil with untreated fibers. Microscopic analysis revealed that the morphology of the treated fiber was denser and free of surface impurities, contributing to its improved performance.

Keywords: Oil palm fiber, Tensile strength, Alkaline solution, Soil stabilization

1. INTRODUCTION

The study of soil and oil palm empty fruit bunch (OPEFB) fiber interactions is a compelling area of research, particularly in terms of improving the geotechnical properties of soil, such as shear strength. In general, the shear strength of fiber-reinforced soil comprises two key elements: the shear strength of the soil matrix and the tensile stress acting on the fibers [15]. Furthermore, the increased shear strength, attributed to the presence of fibers, results from the bond formed between the soil and the fiber within the pull-out mechanism, as well as the inherent tensile strength of the fibers themselves [10]. This mechanism provides a comprehensive understanding of the interplay between soil and fibers, with potential additional interactions when dealing with natural fibers. Notably, natural fibers exhibit a higher water absorption capacity compared to soil [4, 7].

In soft soils, it has been observed that the predominant factor influencing the strength increase in soil mixed with OPEFB fiber is the friction existing between the fiber's surface and the soil [3]. The pressure acting on the soil causes the fibers to stick tightly, and adhesion occurs between the soil and the fibers [1]. Nevertheless, fiber strength remains an important parameter that necessitates testing, especially to determine its durability after extended use in soil. After just 14 d in the soil, the OPEFB fiber strength can reduce up to 50%, and it has been recommended that only 25% of the initial strength be relied upon for long-term use, that is, exceeding 90 d [3]. The degradation of natural fibers is a crucial issue when employing them as construction materials, particularly in soils prone to dampness and changing conditions. Therefore, proactive measures are needed to preserve this strength by applying treatments before introducing them into the soil. It is expected that these treated fibers will exhibit increased resistance within the soil, and hence, would last longer. Therefore, when degradation occurs, the strength of the soil increases with increasing time.

Several methods have been explored to increase the durability of the OPEFB fibers in composites. One approach involves covering the fibers with acrylonitrile butadiene styrene, which effectively shields them from degradation [8]. The application of such a layer has proven effective in reducing fiber absorption by more than 40%, thereby aiding in maintaining the fiber performance, which tends to be constant. Other methods include delignification, which is the initial process of removing lignin from lignocellulosic materials. Delignification encompasses various treatment processes, including biological, physical, chemical, and combined physicochemical treatments. Among these treatments, alkaline, acidic, and organosolve delignification are commonly used for OPEFB fibers [24]. Of these, two alkaline treatments stand out, namely with three chemicals such as ammonia and sodium or calcium hydroxide. The optimal conditions for sodium hydroxide (NaOH) is 1 N at a temperature of 30˚C for 90 min. This results in a substantial reduction in lignin content by 45.8%, a decrease in hemicellulose by 35.6%, and an increase in cellulose by 15.6% [24]. Consequently, the tensile strength of OPEFB fibers treated with NaOH has been reported to exhibit a significant enhancement [17, 18, 21]. Additionally, it was discovered that a 4% (w/v) NaOH solution was the most effective at increasing cellulose, contributing to its tensile strength. Higher than that, the cellulose chain breaks and decreases [20]. A concentration of 4% NaOH is equivalent to 1 N NaOH. Thus, the use of NaOH is also believed to be the cheapest, easiest, and most effective method for reducing lignin, hemicellolusa, and other impurities [20].

In addition to durability, sustainability plays a crucial role when utilizing natural fibers [13]. Based on statistical data from the National Leading Estate Crops Commodity, Indonesia was expected to produce 48.23 million tons of palm oil in 2022 [11]. This production has been consistently increasing year by year, with an average annual growth rate of nearly 10%. Specifically, in South Kalimantan, the production of palm oil reached 1.366 million tons in 2022. Notably, approximately 25% (w/w) of the palm fruit remains leftover in the form of empty palm fruit bunches [19]. Without reducing their function, natural fibers offer the advantages of being environmentally-friendly, locally available, suitability for compositing, cost-effectiveness, and biodegradability [9, 22].

This study aims to test the tensile strength of OPEFB fibers and their durability in soil following treatment with an NaOH solution. Additionally, the OPEFB fibers were incorporated into the soft soil, compacted statically, and subjected to compressive strength testing. Comparative analysis of these test results were conducted in relation to previous studies in which the fibers were not treated [3].

The structure of this article comprises an introductory section, a part highlighting the importance of the research, a section detailing the materials and methods used, a chapter presenting discussing the results, and a concluding section.

2. RESEARCH SIGNIFICANCE

In general, the issue commonly encountered when using natural fibers is their durability, that is, their susceptibility to degradation over time, with this problem also extending to OPEFB fibers. While various studies have explored methods for maintaining/enhancing the durability of these fibers, none have specifically addressed their application in soil stabilization. Therefore, the present study holds significance in developing a treatment method for OPEFB fibers that ensures their durability in soil for a specific duration. The study focuses on assessing the tensile strength, a crucial parameter for stabilizing soil with fibers, to gauge their long-term durability. Furthermore, it investigates the compressive strength of soil-fiber mixtures to gain insights into the prolonged interaction between fibers and soil.

3. MATERIALS AND METHODS

3.1 Fibers and Related Treatments

The fibers utilized in this study were sourced from a palm oil factory located in Angsana Subdistrict, Tanah Bumbu Regency, South Kalimantan Province. To obtain these fibers, empty bunches of fresh palm oil (that have been separated) were peeled to extract the fiber strips, which were subsequently air-dried. The obtained fibers were sorted by length (minimum of 10 cm) and the fiber diameter was measured using a micrometer (prior to testing). The average diameter of the fibers used in this research was 0.257 mm. The fibers were subjected to a treatment process, involving immersion in a 1 N NaOH solution for 90 min [24].

3.2 Soft Soil

The soft soil employed in this study was predominantly clay, with a composition comprising 3.15% sand, 41.52% silt, and 55.32% clay. The specific gravity of the soil was 2.59, with a liquid limit of 60.45%, and a plastic limit of 35.96%. This soil was collected from the same location as in the previous research, specifically from Banyu Hirang Village, Banjar Regency [3].

3.3 Curing of Fiber in the Soil

To assess the durability of the fibers in the soil over a designated timeframe, the fibers were embedded in the soil by placing them in the middle of a statically compacted clay sample. The soil possessed a dry volume weight of 0.92 g/cm^3 and a moisture content of 51%. These density and water content were chosen for consistency with previous research [3]. Two curing conditions were employed, namely, open curing (OC) and close curing (CC). OC aimed to simulate soil conditions that directly interact with open air, allowing changes in soil moisture content. In contrast, CC involved protecting the samples with plastic wrap to maintain a consistent soil moisture content. After the specified duration, the fibers were removed from the soil, washed with tap water, and air-dried.

3.4 Tensile Strength Testing of Fibers

The testing procedures was performed using a specially designed tensile test equipment following the protocols outlined in previous research [3, 6]. The treated fibers were placed in a tensile tester, as depicted in Fig.1. Both ends of the fiber were securely clamped, and a force gauge was connected to a computer to record all force measurements and corresponding time data. Prior to testing, the changes in length were meticulously calibrated, accounting for any tool movement over time [6].

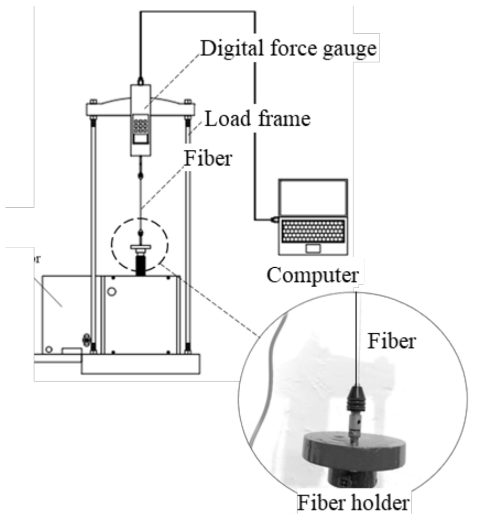


Fig.1 A sketch of tensile testing equipment and fiber holder

3.5 Unconfined Compression Test (UCT) of the Soil-fiber Mixture

Unconfined compression test (UCT) was conducted to determine the impact of NaOH-treated fibers on the compressive strength of the compacted soil-fiber mixture. The UCT is exceptionally well-suited for assessing the efficacy of soil stabilization, particularly when fiber is utilized [2, 3]. The treated fibers, each cut into 1 cm lengths, were mixed with the soft soil, and compacted statically to achieve the same dry volume weight as the previous sample (that is, dry volume weight of 0.92 g/cm^3 and water content of 51%). The amount of fiber added to the soil was 7% on a dry weight basis, which is the optimal percentage of fiber addition in soft soil conditions [5]. Multiple identical samples were prepared and cured under the same two conditions (CC and OC) for testing times of 1, 7, 14, and 28 d. These results were compared with data from previous a previous study [3].

3.6 Characterization of Fiber Morphology

Scanning electron microscopy (SEM) was used to identify the physical alterations depicted in the microphotographs of the longitudinal surface and cross-sections of the untreated and treated fibers. Additionally, changes in the fiber surface morphology were also observed for fibers after curing in the soil for a certain time.

4. RESULTS AND DISCUSSIONS

4.1 Tensile Strength of OPEFB Fiber

Fig.2 illustrates the typical stress–strain curves of untreated and treated OPEFB fibers during the fiber tensile strength testing process. This curve resemble those produced in previous research, where there were three zones, namely, the elastic, plastic, and collapse zones [3], for both the untreated and treated fibers. The test results for each of the five samples suggested that the average tensile strengths of the fiber was 103.88 and 288.22 MPa for the untreated and treated fiber, respectively. The average strains at failure were 9.34 and 12.06% for the untreated and treated fibers, respectively.

These results indicate that the fibers treated with NaOH produce tensile strength 2.77 times higher than those without treatment. This can be attributed to the increase in fiber crystallinity resulting from the NaOH treatment [17]. The strain at the failure of the treated fibers was higher than that of the untreated fibers. These results are in accordance with prior research on the same type of fiber [3].

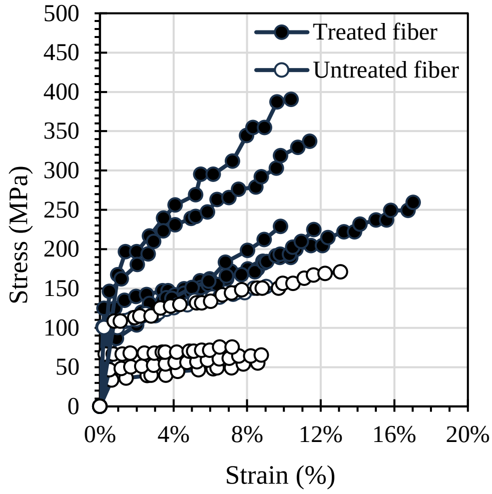


Fig.2 Stress–strain curves of untreated and treated OPEFB fibers

The fiber stiffness in the plastic zone, which is indicated by the slope of the curve in this zone before failure, has rarely been discussed. The average stiffness values of the untreated and treated fibers in the plastic zone were 346.88 and 1525.87 MPa for the untreated and treated fiber, respectively. Besides producing higher tensile strength and strain at failure, NaOH treatment also produces OPEFB fibers that are 4.4 times stiffer.

Fig.3 depicts the stress–strain curves of the fibers treated with NaOH and cured in soil for 1–28 d. Figs 3(a) and 3(b) showcase the OC and CC curves, respectively. In general, the tested fibers displayed the same behavior as the un-embedded samples in the soil, where there were elastic, plastic, and failure zones. In the plastic zone, the strain continued to increase with increasing stress on the different slopes. The fiber breaks upon reaching the maximum strain, and this stress is considered the tensile strength of the fiber, all of which are summarized in Table 1.

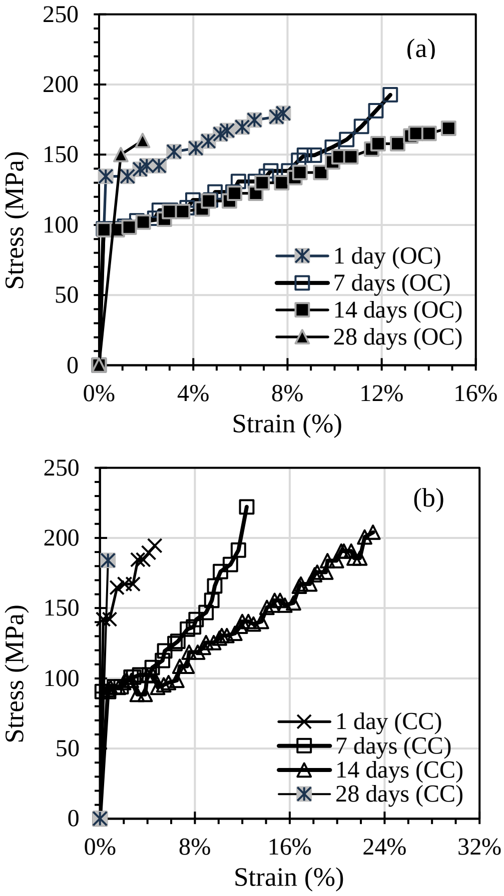


Fig.3 Stress–strain curves of treated fiber after being cured in soil for 1–28 d under (a) opened and (b) closed conditions

As shown in Table 1, the maximum strain of the fiber in the soil increased until day 14 and decreased significantly after day 28. The reduction in the maximum strain at 28 d is related to the very high fiber stiffness; thus, the tensile strength of the fiber tends to remain constant. This phenomenon must be studied further, however, the elasticity of the material also requires attention when using natural fibers. From Table 1, it can be seen that the tensile strength of the treated fiber in the OC was in the range 184.11–194.54 MPa. The tensile strengths of the treated fibers in the CC were 160.2–192.61 MPa.

Table 1. Tensile strength of cured-treated fiber

	Time (day)			
	1	7	14	28
Opened condition				
Tensile strength (MPa)	194.54	222.2	204.02	184.1
Maximum strain (%)	4.64	12.37	23.03	0.68
Plastic stiffness (MPa)	680.15	467.9	519.29	4408
Closed condition				
Tensile strength (MPa)	179.58	192.61	168.88	160.2
Maximum strain (%)	7.82	12.37	14.85	1.86
Plastic stiffness (MPa)	940.44	797.30	604.48	1099

4.2 Tensile Strength of Fiber as a Function of Time

Fig.4 presents the tensile strength of OPEFB fibers as a function of time. Data on the tensile strength of the untreated fibers have been reported in previous research [3]. As shown in the figure, the tensile strength of the untreated fibers decreased with increasing time under both conditions (OC and CC). The tensile strengths of the treated fibers were higher than those of the untreated fibers, with only 30% of the initial strength remaining [3]. Notably, different conditions were used for the fibers treated with NaOH.

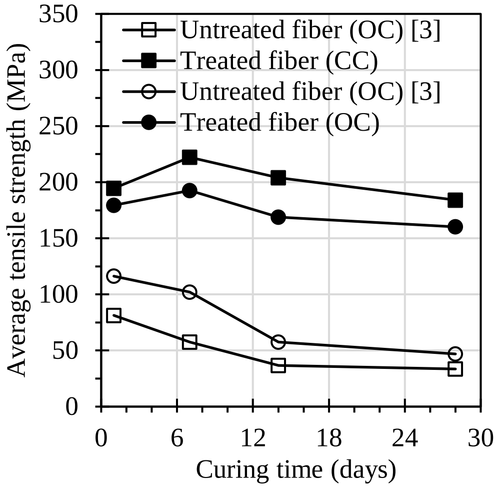


Fig.4 Tensile strength as a function of curing time for the two conditions

As seen in Fig.4, the tensile strength of the treated OPEFB fibers is in the range of 160.2–179.58 MPa for the CC and 184.11–222.2 MPa for the OC. This strength tended not to change significantly during the 28 d when it was kept in the soil. This condition provides a very good opportunity to use tkks fibers treated with NaOH as a natural geotextile material because, apart from being strong, they can also last for quite a long time. The treated tensile strength in the OC was consistently higher than that in the CC for both the treated and untreated fibers. Under CCs with 80% humidity, the number of microorganisms tended to increase [23]. This caused the cellophane fibers to break down more quickly in the closed condition than in the open condition.

However, the tensile strength of the untreated fibers cured in the soil decreased from 116 MPa on the first day to 46.9 MPa (OC) after 28 d of curing in the soil. For samples in CCs, the tensile strength of the fibers decreased from 81.32 MPa on the first day to 33.55 MPa after 28 d in the soil.

4.3 Compressive Strength of Soil-fiber Mixture

Under OCs, reduced water content results in increased negative pore water pressure, which also plays a major role in increasing soil strength [25, 27]. Thus, testing focused on CCs because changes in the sample strength were predominantly caused by the interaction between the fiber and soil [3]. Fig.5 depicts a typical stress-strain relationship for the UCT of soil samples mixed with 7% TKK fiber. Figs. 5(a) and 5(b) showcase the UCT results for the soil cured for 1 and 7 d, respectively. Each condition was represented by three samples. The compressive strength used as the UCT is the compressive strength at a maximum strain of 15% (ASTM-D2166-06, 2013).

From the data, the average compressive strength of samples aged 1 day was 216.7 kPa (untreated fiber) and 247.9 kPa (treated fiber), and 7 d was 236.6 kPa (untreated fiber) and 317.2 kPa (treated fiber). From these data, it can be seen that the fibers can increase the compressive strength of the soil from a soft consistency (q_u<25 kPa) to a very stiff consistency (192–383 kPa). The compressive strengths of the samples mixed with the treated fibers were higher than those of the untreated samples. A higher compressive strength was observed for samples cured for longer periods (i.e., 7 d). This result is consistent with previous research and is attributed to the increase in fiber friction over time in the soil [3]. However, friction studies between the treated fibers and soil need to be conducted.

The elastic modulus (E) is also an important parameter in the discussion of soil and fiber mixtures. From the data in Fig.5, the average E for samples using untreated and treated fiber that was cured for 1 d was 2731.54 and 3318.54 kPa, respectively. After 7 d, the average E values for the untreated and treated fiber were 3770.33 kPa and 3842.86 kPa, respectively. From these data, it was found that the E for soil mixed with treated samples was higher than that for untreated samples. In addition, the concentration in sample E increased over time. This increase in E has also been reported by several researchers who used different types of fibers, such as plastic fibers [16], sisal fibers [26], polypropylene fibers [12], and jute fibers [14].

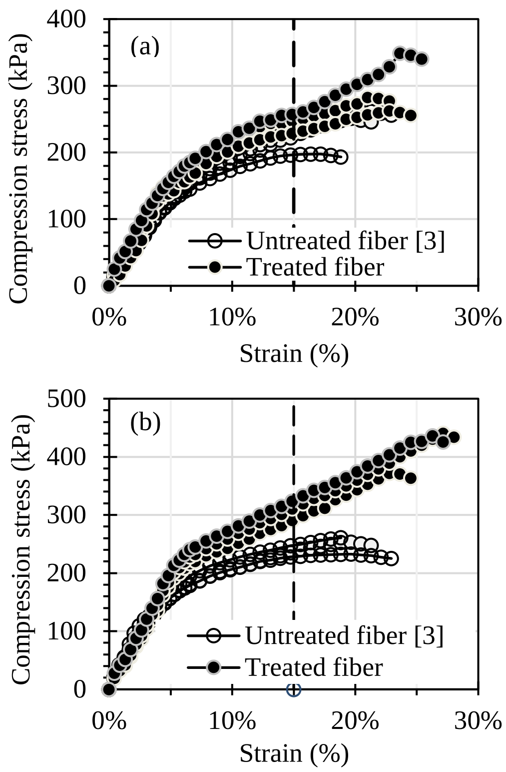
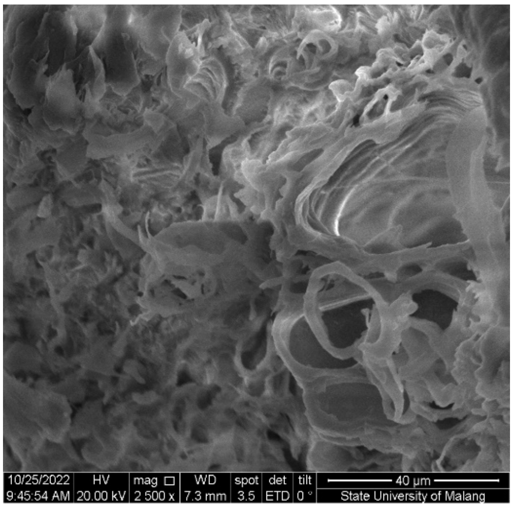


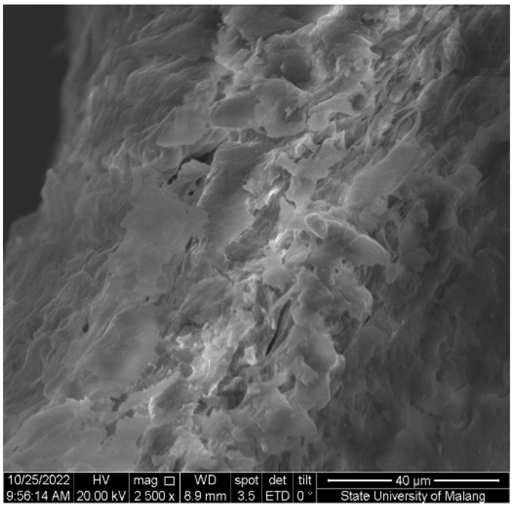
Fig.5 Compression stress and strain of soil mixed with fiber cured in CC for (a) 1 d and (b) 7 d

4.4 Surface Morphology of OPEFB Fiber

Fig.6 shows SEM images of the fiber ends that were not treated with NaOH (Fig.6(a)) and those that were treated with NaOH (Fig.6(b)). As shown in Fig.6(a), the ends of the untreated fibers appeared more porous and the components were not as dense. Under these conditions, cell walls were clearly visible. For those treated with NaOH, the ends of the fibers appeared denser, and the pores and cell walls were not clearly visible at 2500× magnification (Fig.6(b)). Some parts of the OPEFB fiber became more crystalline than amorphous when soaked in NaOH solution [20, 24]. Selolusa plays a role in making the tensile strength of fibers treated with NaOH higher than that without treatment.

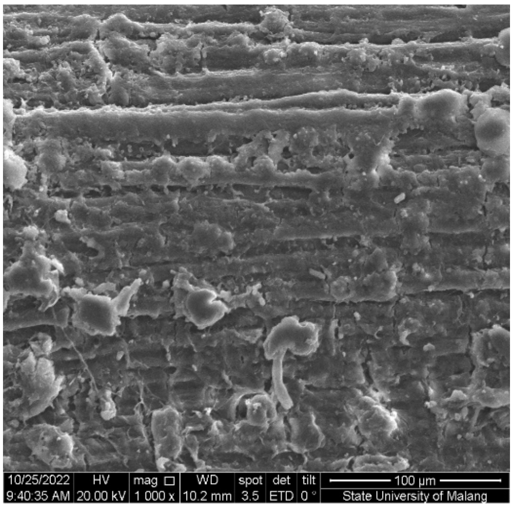


(a)



(b)

Fig.6 Microscopic view of the OPEFB fiber tip for the (a) untreated sample [3] and (b) treated sample



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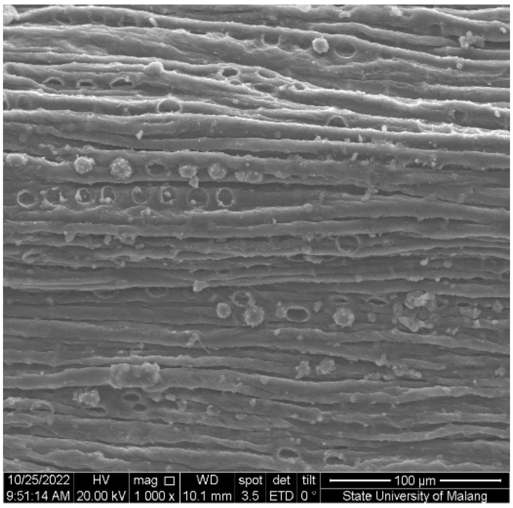
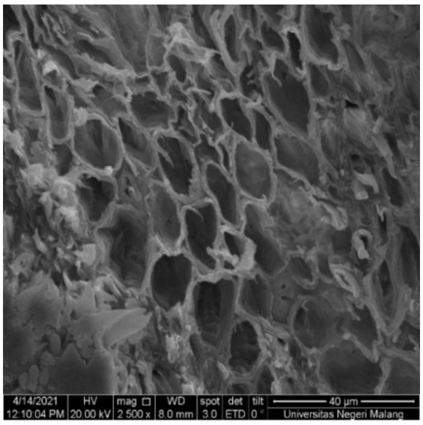


(b)

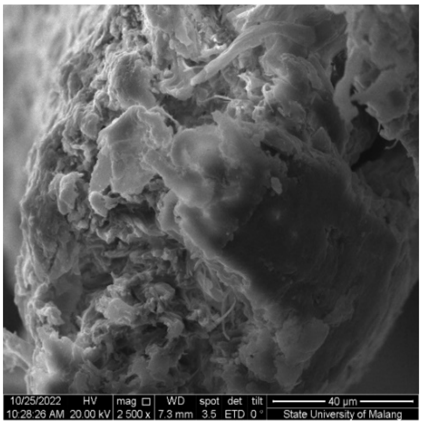
Fig.7 Microscopic surface of longitudinal OPEFB fibers for the (a) untreated sample [3] and (b) treated sample

Figs. 7(a) and 7(b) show the longitudinal surfaces of the OPEFB fibers before and after treatment with NaOH, respectively. As shown in Fig.7(a), the longitudinal surface of the fiber appears to be covered with roughness. Before the treatment, the fiber surface contained wax, impurities, and fatty materials [17]. Meanwhile, the treated fiber in Fig.7(b) appears cleaner, with the fiber being more clearly visible. Some silica bodies were also clearly visible, whereas others were separated, producing small holes on the fiber surface. The clean surface of the fiber results in better adhesion between the fiber and other materials [17]. This caused the compressive strength of the soil to which the treated fiber was added to be higher than that of the soil without treatment. Moreover, the friction component between fiber and soil is one of the components that plays a role in increasing the compressive strength of the soil-fiber mixture [3].

Figs. 8(a) and 8(b) show the microscopic morphologies of the broken ends of the untreated and treated fibers, respectively, after the tensile strength test. These two fibers were cured in soil for 7 d before being subjected to tensile testing. In Fig.8(b), the cell walls are clearly visible, depicting a part of the fiber that is more porous than that which has not been cured in the soil (Fig.6(a)). This condition caused the tensile strength of the untreated fiber to decrease, especially in the first 7 days. In contrast to the treated fibers, even though they were cured in the soil for 7 days, the ends of the fibers did not change significantly, remaining as dense as the fibers that had not been cured in the soil (Fig.6(b)). This resulted in the tensile strength of the fibers not changing significantly. The results indicate a significant correlation between the quality of the fiber microstructure and its tensile strength.



(a)



(b)

Fig.8 Microscopic view of the OPEFB fiber tip after 28 d in an (a) untreated sample [3] and (b) treated sample

5. CONCLUSIONS

The tensile strength and microscopic morphology of the fibers treated with alkali were analyzed. Several conclusions were drawn, including:

1. The average tensile strength of the NaOH-treated fiber was 288.22 MPa. This tensile strength is 2.77 times higher than that without treatment (i.e., 103.88 MPa).
2. The stiffness in the plastic zone also increase of 4.4 times after the EFB fibers were treated with NaOH.
3. With increasing time, the tensile strength of OPEFB fibers treated with NaOH ranged between 160.2–179.58 MPa (closed condition) and 184.11–222.2 MPa (open condition). Meanwhile, the tensile strength of the untreated fibers decreased with increasing time in both open and closed conditions.
4. In general, the tensile strength of the fibers in the soil in the open condition was higher than that in the closed condition for both treated and untreated conditions.
5. Soil with fiber increased its compressive strength from the consistency of soft soil (q_u<25 kPa) to 247.9 kPa at 1 day of age and 317.2 kPa at 7 days of age (very stiff consistency).
6. The SEM results show that the surface morphology of the fibers treated with NaOH was denser and cleaner than those without NaOH treatment.

6. ACKNOWLEDGMENT

This research was funded by the University of Lambung Mangkurat through the *PDWM* (Contract No. 063.12/UN8.2/PG/2023).

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