From: Geomate Editor
Sent: 16 October 2022 9:53
To: y.arifin@ulm.ac.id; emarsyad@ulm.ac.id; rudisiswanto@ulm.ac.id; ikomangtrifebiastawa69@gmail.com
Subject: 3610: Review Results : Int. J. of GEOMATE---

Dear Authors,

Thanks for your kind contribution. We have reviewers' comments on your paper (attached). Please send the revised paper by a maximum of 2 weeks upon receiving this email. Please send responses to reviewers by authors in separate files. An example of "response to reviewers by authors" is attached. Please use the following link:

Revised Paper Submission Link:
https://form.jotform.com/geomate/journal-revised-paper

Best regards.

Dr. Zakaria Hossain (Ph.D. Kyoto Univ.)
Professor, Mie University, Japan
Editor-in-Chief, Int. J. of GEOMATE
editor@geomate.org

Monday, October 3, 2022

GEOMATE Journal Review and Evaluation

Paper ID number	3610
Paper Title	TENSILE STRENGTH AND DURABILITY OF OIL PALM EMPTY FRUIT BUNCH FIBER IN SOFT SOIL
Originality	Good
Quality	Average
Relevance	Average
Presentation	Average
Recommendation	2. Accept with minor revision

Mandatory changes

the paper needs major revision. Some revision about

this abstract isn't clear and need to be improved with consist
1. background
2. objective
3. material &method
3. result & discussion
4. Conclusion.

please to the point what is the novelty of the research..

standard test please mentioned at the manuscript

format needs to be improved.

figure 6 and 7 in KPa but at tables 1 and 2 in MPa..could you give an explanation?

figure 7.b has been not explained yet.

figure 6 and 7 is similar but figure 6 spread to 6.a and 6.b, why is this pattern didn't applied in the figure 7...?

grammar needs to be improved.

the formatting needs to double check.
Explanation at the result and discussion section but figure at the conclusion

The conclusion needs to simplify and for all figures please switch to the result and discussion section.

detail comment can be seen at the attachment

Upload file (if any)

pdf 3610 paper rev.pdf

Reviewer's E-mail (Remove before sendiing to author)

Wednesday, October 5, 2022

GEOMATE Journal Review and Evaluation

Paper ID number	3610
Paper Title	TENSILE STRENGTH AND DURABILITY OF OIL PALM EMPTY FRUIT BUNCH FIBER IN SOFT SOIL
Originality	Good
Quality	Good
Relevance	Good
Presentation	Good
Recommendation	2. Accept with minor revision

General comments

The data is not complete. All the data of this research should be provided and the authors should give a sufficient comments and analysis.
The outline of the figures have to be deleted
the X and Y axis line in all Figures are outline. It should be there in clear line, X and Y only
give the photograph of making process, tensile and compressive specimen and testing dial, because the tensile strength were very high compared to those in concrete
The amount of figures (graph results is not sufficient for an international journal), the author gives only 20 figures, at least 30 figures
remove all the references below 2018 and give the 2018-2022 instead.

Mandatory changes

The data is not complete. All the data of this research should be provided and the authors should give a sufficient comments and analysis.
The outline of the figures has to be deleted
the X and Y axis line in all Figures are outline. It should be there in clear line, X and Y only
give the photograph of making process, tensile and compressive specimen and testing dial, because the tensile strength were very high compared to those in concrete
The amount of figures (graph results is not sufficient for an international journal), the author gives only 20 figures, at least 30 figures
remove all the references below 2018 and give the 2018-2022 instead.

Suggested changes

The following references should be added:

Noaman, M. F., Khan, M. A., & Ali, K. (2022). Effect of artificial and natural fibers on behavior of soil. Materials Today: Proceedings.
Moslemi, A., Tabarsa, A., Mousavi, S. Y., & Monfared, M. H. A. (2022). Shear strength and microstructure

characteristics of soil reinforced with lignocellulosic fibers-Sustainable materials for construction. Construction and Building Materials, 356, 129246.
Boobalan, S. C., & Devi, M. S. (2022). Investigational study on the influence of lime and coir fiber in the stabilization of expansive soil. Materials Today: Proceedings.
Tran, K. Q., Satomi, T., & Takahashi, H. (2018). Effect of waste cornsilk fiber reinforcement on mechanical properties of soft soils. Transportation Geotechnics, 16, 76-84.
Wei, L., Chai, S., Xue, M., Wang, P., & Li, F. (2022). Structural damage and shear performance degradation of fiber–lime–soil under freeze–thaw cycling. Geotextiles and Geomembranes, 50(5), 845-857.
Kumar, N., Kandasami, R. K., & Singh, S. (2022). Effective utilization of natural fibres (coir and jute) for sustainable low-volume rural road construction–A critical review. Construction and Building Materials, 347, 128606.
Sharma, N. K. (2022). Utilization of fly ash, lime sludge and polypropylene fiber as stabilizers to enhance soil properties. Materials Today: Proceedings.
Ramakrishna, G. (2022). Oil Palm Empty Fruit Bunch Fiber Surface Morphology, Treatment, And Suitability As Reinforcement In Cement Composites: A State Of The Art Review. Cleaner Materials, 100144.
Zhang, J., Deng, A., & Jaksa, M. (2021). Enhancing mechanical behavior of micaceous soil with jute fibers and lime additives. Journal of Rock Mechanics and Geotechnical Engineering, 13(5), 1093-1100.
Jawaid, M., Chee, S. S., Asim, M., Saba, N., & Kalia, S. (2022). Sustainable kenaf/bamboo fibers/clay hybrid nanocomposites: Properties, environmental aspects and applications. Journal of Cleaner Production, 330, 129938.
Madhavan, M. K., Sathyan, D., & Jayanarayanan, K. (2021). Hybrid natural fiber composites in civil engineering applications. In Hybrid Natural Fiber Composites (pp. 41-72). Woodhead Publishing.

Reviewer's E-mail (Remove before sendiing to author)

Tuesday, October 11, 2022

GEOMATE Journal Review and Evaluation

Paper ID number	3610
Paper Title	Tensile strength and durability of oil palm empty fruit bunch fiber in soft soil
Originality	Good
Quality	Good
Relevance	Average
Presentation	Average
Recommendation	2. Accept with minor revision

General comments

The article is very interesting however needs to be modified and revised to be more quality and appropriate. The abstract section should be improved by adding a clear problem statement. Keywords should be changed and choose the appropriate keyword that reflects to the article. The introduction section should be improved by explaining the clear problem statement. SEM results and data should be situated in the result and discussion section rather than in the conclusion. Lastly, the conclusion section should be improved by referring to the result and discussion.

Mandatory changes

The location of the figures and tables should be situated after the paragraph that mentioned about them. For other comments please refer to the pdf file.

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Saturday, October 15, 2022

GEOMATE Journal Review and Evaluation

Paper ID number	3610
Paper Title	TENSILE STRENGTH AND DURABILITY OF OIL PALM EMPTY FRUIT BUNCH FIBER IN SOFT SOIL
Originality	Average
Quality	Average
Relevance	Average
Presentation	Average
Recommendation	2. Accept with minor revision

Mandatory changes

If the Younge's modulus of the soil's samples from the results of UCT analysed, this would robust the results more.

Reviewer's E-mail (Remove before sendiing to author)

Response by Authors to Reviewer's Remarks/Comments

TENSILE STRENGTH AND DURABILITY OF OIL PALM EMPTY FRUIT BUNCH FIBER IN SOFT SOIL

Authors: Yulian Firmana Arifin, Muhammad Arsyad, Rudi Siswanto, I Komang Tri Febi Astawa, Muhammad Hafizhi Ridha, Muhammad Rafiqi Ramadhani

Authors would like to thank the reviewers who have provided input, corrections, and comments on the contents of the article. Authors have made some changes and additions to the article as suggested by all the reviewers. Here are the authors' comments given to follow up on all these suggestions.

No.	Reviewer A's Comments	Author Response
1	This abstract isn't clear and need to be improved with consist 1. background 2. objective 3. material &method 3. result & discussion 4. Conclusion.	The abstract has been revised, especially in the background section. This section is continued by objectives, materials, methods, and results as suggested by the reviewers. Please see page 1 in line 11–16.
2	Please to the point what is the novelty of the research	The novelty of this study is the endurance of OPEFB fiber in the soil, including the beginning of reduction in strength and the quantity of remaining strength. Although tensile strength has been extensively recorded, friction between fiber and soil has never been reported, despite the fact that it is a crucial component of fiber-based soil stability. This topic is addressed in page 1 lines 54–58.
3.	Standard test please mentioned at the manuscript	Test standards have been added for each test in page 2 lines 93, 96, and 97 (2nd column), page 3 lines 22 and 26 (1st column).
4.	Format needs to be improved.	The format has been adjusted to the template provided on the journal website. Thank you for the reviewer's notification.
5.	Figure 6 and 7 in KPa but at tables 1 and 2 in MPa..could you give an explanation?	Tables 1 and 2 are a summary of Figures 5 and 6, respectively. References generally use the MPa unit for this test result because of its very high value. For ease of comparison made with the same unit. While the units in Figures 7 and 8 (formerly, Figures 6 and 7) use kPa to match the results in that range. There are no special rules for this.
6.	Figure 7.b has been not explained yet.	Figure 8 (Figure 7 in the previous version) has been described starting in page 5, line 13. The graph shows the relationship between the time and compressive strength. The figure also

		shows the relationship of the weight change, i.e., the process of reducing water in the samples cured under open conditions.
7.	Figure 6 and 7 is similar but figure 6 spread to 6.a and 6.b, why is this pattern didn't applied in the figure 7...?	Figure 7 and Figure 8 (Figures 6 and 7 in the previous version) show different graphs. Figure 7 shows the relationship between stress and strain in UCT testing. Figure 8 shows the compressive strength as a function of curing time, which is the maximum value of compressive stress, or stress at a maximum strain of 15% according to ASTM D 2166.
8.	Grammar needs to be improved	All the writers are not native speakers, so for checking and correcting the language, we use the services of Editage. The article has been resubmitted for review as part of the service. The certificate is attached.

Response by Authors to Reviewer’s Remarks/Comments

TENSILE STRENGTH AND DURABILITY OF OIL PALM EMPTY FRUIT BUNCH FIBER IN SOFT SOIL

Authors: Yulian Firmana Arifin, Muhammad Arsyad, Rudi Siswanto, I Komang Tri Febi Astawa, Muhammad Hafizhi Ridha, Muhammad Rafiqi Ramadhani

No.	Reviewer B’s Comments	Author Response
1	The data is not complete. All the data of this research should be provided and the authors should give a sufficient comments and analysis.	The author has added some data as suggested by the reviewer after each figure. Additional comments and analysis have been made after the data mentioned . Thank you for the advice from the reviewer so that this article can be more complete.
2.	The outline of the figures have to be deleted	The graphic outline was removed and presented per reviewer suggestion.
3.	The X and Y axis line in all Figures are outline. It should be there in clear line, X and Y only	The X and Y charts have been adjusted and redefined per reviewers' recommendations.
4.	Give the photograph of making process, tensile and compressive specimen and testing dial, because the tensile strength were very high compared to those in concrete.	The photographs have been added to the article in Figure 3. The results of the tensile stress test have been compared to those given in the literature, as discussed in page 4, lines 16–26.
5.	The amount of figures (graph results is not sufficient for an international journal), the author gives only 20 figures, at least 30 figures.	The author has met the requirements set by the journal in Publishing Agreement Q.14, which is to have at least 8 figures and/or tables.
6.	Remove all the references below 2018 and give the 2018-2022 instead	The author has removed some references under 2018 and left those that are still deemed necessary. The author has also added all the references suggested by the reviewer in all parts of the article from the introduction to the discussion. Thank you for this very valuable advice.

Response by Authors to Reviewer's Remarks/Comments

TENSILE STRENGTH AND DURABILITY OF OIL PALM EMPTY FRUIT BUNCH FIBER IN SOFT SOIL

Authors: Yulian Firmana Arifin, Muhammad Arsyad, Rudi Siswanto, I Komang Tri Febi Astawa, Muhammad Hafizhi Ridha, Muhammad Rafiqi Ramadhani

No.	Reviewer C's Comments	Author Response
1.	The abstract section should be improved by adding a clear problem statement	The abstract has been improved by adding a problem before the objective of this research. Please see page 1 in line 11–16.
2.	Keywords should be changed and choose the appropriate keyword that reflects to the article.	Keywords have been replaced with the words discussed in the article. There are two words added, namely durability and OPEFB.
3.	The introduction section should be improved by explaining the clear problem statement.	A clear problem statement has been added to the article in page 1 line 54–58.
4.	SEM results and data should be situated in the result and discussion section rather than in the conclusion	The explanation of the SEM results has been carried out in page 8 line 1–42.
5.	the conclusion section should be improved by referring to the result and discussion.	The conclusion has been improved as suggested by the reviewer.

Response by Authors to Reviewer's Remarks/Comments

TENSILE STRENGTH AND DURABILITY OF OIL PALM EMPTY FRUIT BUNCH FIBER IN SOFT SOIL

Authors: Yulian Firmana Arifin, Muhammad Arsyad, Rudi Siswanto, I Komang Tri Febi Astawa, Muhammad Hafizhi Ridha, Muhammad Rafiqi Ramadhani

No.	Reviewer D's Comments	Author Response
1.	If the Younge's modulus of the soil's samples from the results of UCT analysed, this would robust the results more.	Young's modulus of soil-fiber samples has been added to Figure 9 and discussed in page 6 lines 47–74 (2nd column).

International Journal of GEOMATE, Month, Year Vol.00, Issue 00, pp.000-000
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2022.000.0000
Geotechnique, Construction Materials and Environment

TENSILE STRENGTH AND DURABILITY OF OIL PALM EMPTY FRUIT BUNCH FIBER IN SOFT SOIL

Yulian Firmana Arifin[1, 2], *Muhammad Arsyad[2], Rudi Siswanto[3], I Komang Tri Febi Astawa[2], Muhammad Hafizhi Ridha[2], Muhammad Rafiqi Ramadhani[2]

[1] Wetland Based Material Research Center, University of Lambung Mangkurat, Banjarbaru, Indonesia;

[2] Civil Engineering Study Program, University of Lambung Mangkurat, Banjarbaru, Indonesia;

[3] Mechanical Engineering Study Program, University of Lambung Mangkurat, Banjarbaru, Indonesia

*Corresponding Author, Received: 00 Oct. 2018, Revised: 00 Nov. 2022, Accepted: 00 Dec. 2022

ABSTRACT: Natural fibers are already being used to stabilize soil. However, the exact mechanism by which natural fibers improve the shear strength of soil is still not clear, and it varies according to the morphology of each fiber. Its durability in soil is also an important issue in the use of natural fibers for soil stabilization. This study focused on the strength and durability of oil palm empty fruit bunch (OPEFB) fiber as a stabilizing material for soft clay. The durability was determined according to the changes in tensile strength and friction of the soil after a certain period. The clay was obtained from Banyu Hirang in South Kalimantan. The OPEFB fiber was obtained without further treatment from a palm oil processing plant. Tensile, soil-fiber friction, and unconfined compression tests were conducted for mixtures of fiber and soil. Preparations were made for each test with the same duration and conditions (1, 7, 14, 28, and 90 days) in closed and open conditions. The results showed that the average tensile strength of the fiber before use was 101 MPa. This value decreased sharply after 14 days in the soil, leaving a strength of 35.71 MPa in the open condition and 23.89% in the closed condition on the 90th day. The soil-fiber friction increased with increasing time, reaching 0.15 MPa in both conditions from the initial value of 0.06 MPa. The compressive strength of the soil-fiber mixture also increased with time. The corresponding scanning electron microscope results strengthened the findings of this study.

Keywords: Tensile strength, Durability, Soft soil, Fiber, OPEFB.

1. INTRODUCTION

In addition to concrete, synthetic or natural fibers can be used for soil stabilization. The synthetic fibers presently being used include strands of waste tires [1], nylon fibers [2], polypropylene fibers [3–5], glass fibers [6], and basalt fibers [7]. The emerging natural fibers include coir fiber [8], wheat straw, barley straw, wood shavings [9], bamboo fiber [10], and oil palm empty fruit bunches (OPEFBs) [11,12]. In contrast to synthetic reinforcements such as geotextiles and geogrids, fiber reinforcements can be easily implanted for slope improvement and thin-layer reinforcement in field applications [13]. The inclusion of fibers is an efficient method for decreasing the cement content of collapsible soils [3]. Wu et al. [14] reported that natural fibers contribute not only to reinforcement, but also to protection against slope soil losses and riverbed erosion; they can also provide filtration or drainage for eliminating heavy metals.

Soil stabilization with fiber is influenced by many factors, including the amount of fiber [1,2,4–7,9,10,12,15,16], fiber length [5,7,10,15], moisture contents of the samples [16], fiber characteristics [6,9,12,17], fiber diameter [10], soil properties [2,17], and soil stress [1,8,17]. In some cases, natural fibers can absorb sufficient quantities of water [9,18,19]. This causes an increase in the fiber's moisture content, resulting in poor interface adhesion between the fiber and composite material [19]. Arifin et al. [11,20] found that a 7% OPEFB fiber absorbed water, allowing soft soil to be further compacted. Consequently, the compressive strength increased. In general, this tendency is particularly important for the stabilization of soft, high-water-content soils.

Although they have been widely studied, the interactions between soil and fiber remain very interesting for improving the geotechnical properties of soils. The shear strength of a fiber-reinforced soil comprises two components: the shear strength of the soil matrix and the tensile stress acting on the fiber [13]. In addition, the contribution of the fiber to the increase in shear strength is caused by the bonding of the soil and fiber in the pull-out mechanism as well as the tensile strength of the fiber itself [16]. These mechanisms explain the interactions between the soil and fiber in general, but other interactions may occur between the soil and fiber, especially natural fibers. However, it is still unclear which of the two mechanisms—the shear of the soil matrix with the fiber or the tensile strength of the fiber—is the most important. This means that the tensile strength and soil-fiber friction must be tested to determine how they affect the shear strength of the soil after mixing.

It is also important to test the tensile strengths of natural fibers to obtain a cheap and lightweight composite material for withstanding loads [21]. In previous studies, natural fibers such as vakka, date palm stems, and bamboo were tested and compared with other fibers such as sisal, banana stem, coconut, and oil palm. It was not explained where the palm fiber was sourced from. The order of fiber tensile strength from largest to smallest was date palm, bamboo, oil palm, coconut, vakka, sisal, and banana fiber. From reference, data on 23 natural fibers, including data on the tensile strengths of fibers such as coir (15–500 MPa), sisal (31–640 MPa), jute (29–773 MPa), and kenaf bast (18–476 ± 46 MPa) were collected and summarized by Ali [22]. The tensile strength of these fibers was very high. The tensile strength of OPEFB is reported to vary widely, even though tensile strength is a basic parameter that is directly related to other parameters. It has been reported as being in the range of 60–81 MPa [18], 74.4 MPa [23], and 21–260 MPa [24].

Besides functioning as synthetic fibers, natural fibers have the advantages of being environmentally friendly [25], locally available, able to become composites with cement or lime, inexpensive, and degradable [2,24,26]. The degradation of natural fibers is an important issue in their use as construction materials, especially in soils that tend to be moist and whose conditions can change. The fiber resistance allows for the bonds in the soil to be strengthened over time, such that when the fiber is degraded, the soil strength increases. However, there is no information on the resilience of OPEFB fibers in soils over time, so testing is required.

In addition to durability, another aspect that must be considered in the use of natural fibers is sustainability [27]. Based on data from the Directorate General of Plantations, a total of 49.71 million tons of palm oil production occurred in Indonesia in 2021 [28]. This production continues to increase annually, with an average annual increase of 9.88%. In South Kalimantan, 1.6 million tons of palm oil are produced. The remaining production, in the form of empty oil palm fruit bunches by weight, is approximately 25% of the fruit [29]. This shows the large amount of this fiber available in South Kalimantan and Indonesia.

The problem statements of this study are what mechanism most influences the stabilization of soft clay utilizing fiber and how much do the tensile strength of OPEFB fiber and its friction stress with soil change over time in the soil. This study aimed to test the strength of the OPEFB fiber (including the tensile strength), along with its friction with the soil and resistance in the soil. There was no reference for the curing time for the resistance of this fiber, so the test used a maximum of 90 days, according to the planned duration of the study. The OPEFB fiber was an untreated fiber intended to attain the starting conditions before being treated.

2. RESEARCH SIGNIFICANCE

OPEFB fiber is still relatively new in construction, especially for soil stabilization. The data obtained is expected to provide references to important components, namely the tensile strength and friction of natural fibers with the soil. The results of this study clarify the fiber contribution in the context of increasing soil strength from these two components. Besides strength, an important issue of OPEFB fiber is its resistance in the soil. After a certain time, the remaining strength of the two components provides important information on the design of the reinforcement.

3. MATERIALS AND METHODS

3.1 Materials

The materials used in this study were soft soil and OPEFBs. Clay was obtained from Jl. Governor Sarkawi, Banyu Hirang, Gambut, Banjar Regency, South Kalimantan. The clay had an initial moisture content of 56% and a specific gravity of 2.31. The liquid limit, plastic limit, and soil plasticity index (ASTM D 4318) values were 61%, 34.87%, and 26.13%, respectively. The soil contained a fine content of 95.12% and a clay content of 56.32% (ASTM D7928). According to the Unified Soil Classification System (USCS) (ASTM D2487), the soil was classified as organic clay (OH) soil.

The OPEFB was a waste product from palm oil mills at Kec. Angsana, Kab. Tanah Bumbu, South Kalimantan Province. The fiber was taken from the OPEFBs. Figure 1 shows fiber preparation from the row material of an empty fruit bunch (Figure 1(a)) to the fine fiber. OPEFB was shredded until the crude fiber was obtained (Figure 1(b)). These fibers are then separated and air dried to obtain the fine fibers (Figure 1(c)).

In this study, no treatment was performed on the fibers before testing. To maintain the consistency of the results, fibers were selected with diameters between 0.4–0.6 mm. A digital micrometer was used to measure the fiber diameter. The measurements were performed at three points (i.e., both ends and in the middle), and the average of the three measurements was used. This was because the natural fiber cross-section is not uniform along the length of the fiber and varies within a fiber bundle [30]. This diameter was considered when determining the stress occurring when calculating the tensile stress.

Fig. 1 Fiber preparation from the row material of an empty fruit bunch to the fine fiber (a) oil palm empty fruit bunch (OPEFB), (b) empty fruit bunch shredded fiber, and (c) final fiber as used.

3.2 Sample Preparation and Testing

The sample consisted of soil that had been supplemented with fiber at the optimal percentage, as determined by previous studies [11,12]. Based on the results of previous studies, the compacted soil sample with the fiber had a dry volume weight (γ_d) of 0.92 gr/cm^3 and a moisture content of 51%. The optimum fiber content was 7%. The length of the fiber was adjusted to the diameter of the sample. For the unconfined compression test (UCT) (ASTM-D2166), a length of 10 mm was used, and for a compaction test, a length of 100 mm was used. Tensile tests were conducted on untreated samples soaked in the soil. The compaction was performed using a standard Proctor (ASTM D698), and the fibers were placed in each layer of the compaction. After compaction, the samples were placed in a layer of soil and allowed to stand for 1, 7, 14, 28, and 90 days under two conditions: an open condition (i.e., allowed to interact with the atmosphere) and a closed condition (i.e., coated with plastic wrap so that there was no change in the moisture content of the samples). These conditions indicated whether the soil was dry (above the water table) or moist (below the water table), and were expected to affect the durability of the fibers. At the specified time, the fibers were removed, cleaned, and tensile-tested. The tensile test equipment and its settings are shown in Figure 2(a).

In addition to the tensile strength, the friction between the fiber and soil is an important component in their interactions; thus, it was also tested. A mold was specially designed to perform static compaction to achieve the same density as in the UCT test (i.e., 0.92 g/cm^3 with 51% moisture content) where the fibers were not cut, as shown in Figure 2(b). The shear test was performed using the same tool as in the tensile test by modifying the bottom part, as shown in the inset of Figure 2(a).

Figure 3(a) depicts a test sample of the fiber put on a tensile apparatus. This effect is obtained if the fiber breaks at the center of the span rather than in the pinched fiber region, as illustrated in Figure 3. (b). Figure 3(c) shows the implementation of UCT on a soil sample mixed with fiber. The compressive strength taken is the compressive stress at its maximum value or at 15% strain.

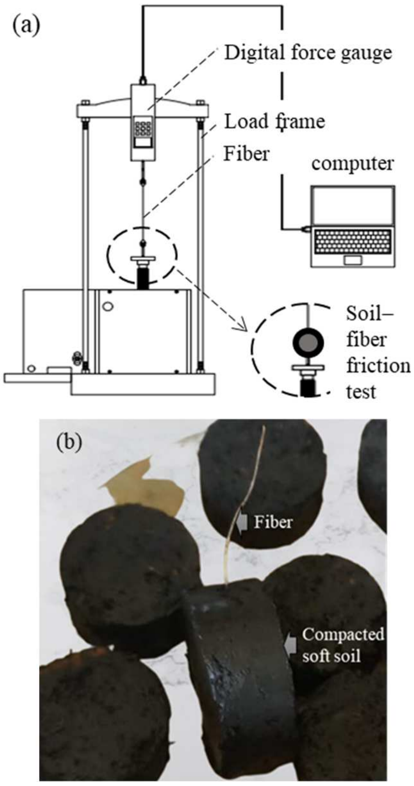

Fig. 2 Tensile and friction soil–fiber tests (a) equipment sets, and (b) soil–fiber friction samples.

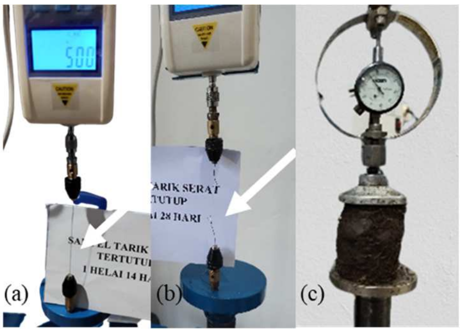

Fig. 3. (a) Pulling fiber tensile test; (b) fiber breaking; and (c) soil and fiber samples after UCT

Physically, the samples were evaluated by using scanning electron microscopy (SEM) to determine the impact of long-term fiber exposure on the tensile strength and friction between the soil and fiber. Researchers have used SEM to study the microscopic shapes of several natural fibers suggested as building materials ([31][18][32]).

4. RESULTS AND DISCUSSIONS

4.1 Tensile Stress of the OPEFB

Figure 4 shows typical results from the OPEFB fiber tensile test in this study. This curve is similar to that reported by Omar et al. [23], where three regions are generated: elastic, plastic, and fracture regions. The fiber begins to be pulled into the elastic region at a strain of 0.06%–0.08%, resulting in a tensile stress of 60–70 MPa. This strain is higher than that reported by Ramlee et al. [18] (0.03%) and Omar et al. [33] (0.04%). Moreover, it continues in the plastic region until the 5%–6% strain reaches a tensile stress of 97–107 MPa (mean of 101 MPa). In addition, the tensile strength obtained in this study exceeds that reported by Ramle et al. [18] and Omar et al. [33]. The tensile strength obtained in this study is close to that reported by Danso (i.e., 110 MPa) [34] and less than that summarized by Rao and Ramakrishna (i.e., 283 MPa) [24]. The age of the parent plants, the age of the fiber after extraction, fiber surface condition (cell wall peel off, skin damage, surface treatments), gauge length, and grip pressure fluctuation during testing all contribute to this variation [24].

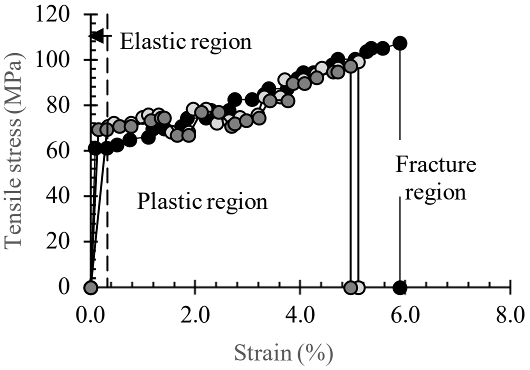

Fig. 4 Typical tensile test result.

4.1.1 Tensile strength of fiber as a function of time

Figure 5 shows the results from the tensile tests of the fibers soaked in the soil under the open and closed conditions. The values are listed in Table 1. The tensile strength decreases from 98.59 MPa on day 1 to 40.82 MPa on day 28. By 90 days, the tensile strength decreases by 5.10 to 35.71 MPa at a rate of 0.08 MPa/day.

Figure 5 also shows that the fiber in the open state has a higher tensile strength (by 10–26 MPa) than that in the closed state. The smallest difference in the 14-day cure time is approximately 6 MPa. This difference might be owing to large variations in the physical and chemical conditions of the natural fibers in the bunch even though they are taken from the same plant; this also affects their mechanical properties, including the tensile strength [30,35]. The application conditions also affect the tensile strength, as shown in Figure 4. It is very likely that cellulose, the most influential component of the fiber tensile strength, degrades more in the closed state. In aerobic, nutrient-rich water, fibers decompose quickly, whereas previously dried fibers disintegrate more slowly [36]. In addition, the moisture affects the microorganism's development and multiplication. This is especially true for fungi, which grow quickly on cellulosic fibers when the humidity is high (approximately 80%) [37]. In general, natural fibers decompose naturally. This is advantageous when using natural fibers, as they are low in pollution. However, for long-term use, efforts must be made to maintain the strength over time. Further research is needed, especially regarding their use in soils.

Based on Table 1, the residual tensile strength after 90 days can be determined from one unit minus the percentage reduction to obtain 36.22% and 28.13% for open and closed conditions, respectively. As these numbers tend to be stable, it is safe to utilize approximately 25% of the fiber's tensile strength for calculating long-term use in the soft soil.

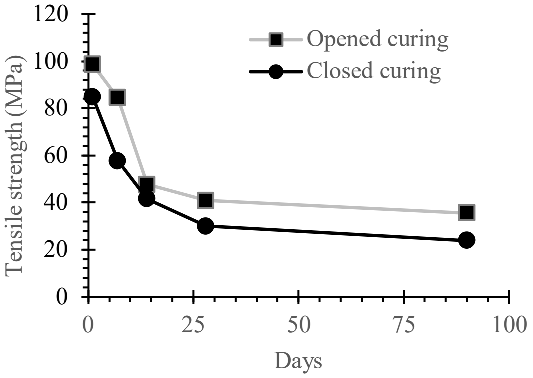

Fig. 5 Tensile strength of fiber as a function of curing time.

Table 1 Tensile strength of fiber over time with two different conditions

Time	Open curing				Closed curing			
Day	MPa	MPa	%	Rate/day	MPa	MPa	%	Rate/ day
1	98.59				84.92			
7	84.51	14.08	14.29	2.35	57.72	27.20	32.03	4.53
14	47.62	50.97	51.70	5.27	41.59	43.33	51.02	2.30
28	40.82	57.78	58.60	0.49	29.97	54.95	64.71	0.83
90	35.71	62.88	63.78	0.08	23.89	61.04	71.87	0.10

4.1.2 Soil-fiber friction as a function of time

Figure 6 shows the friction results for the soil fibers as a function of time. As shown in the figure, the friction increases from day 1 to day 7. On day 1, both conditions produce the same friction, namely 0.06 MPa. Furthermore, in the first 7 days, the friction increases by 0.07 MPa (i.e., 111.11%) for the exposed soil, as shown in Table 2. For the closed sample, the friction increase is slightly smaller at approximately 0.05 MPa or 73.33%. A quite large increase continues to occur until day 14, with an increase of 0.01 and 0.02 MPa for the samples with open and closed conditions, respectively. The interactions between the fiber and soil can be seen in this test, especially in the first 7 days. The resulting friction is greater because large quantities of fiber interact with the soil. To maintain the interactions between the soil and fiber, the amount of fiber being used is limited. Arifin et al. [11,20] found that 7% fiber on a dry-weight basis was the optimum condition for soft clay soils. Notably, the vertical compressive strength decreases as a result of the high number of fiber-to-fiber contacts.

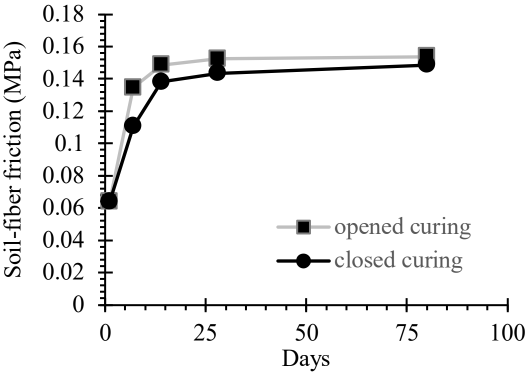

Fig. 6 Soil-fiber friction as a function of curing time.

Table 2 Soil-fiber friction as a function of time

Time	Opened curing			Closed curing		
Day	MPa	MPa	%	MPa	MPa	%
1	0.06			0.06		
7	0.13	0.07	111.11	0.11	0.05	73.33
14	0.14	0.08	133.33	0.14	0.07	116.67
28	0.15	0.09	139.00	0.14	0.08	125.00
90	0.15	0.09	141.67	0.15	0.08	133.33

4.1.3 Unconfined compressive strength of stabilized clay

Figure 7 shows the UCT results for a clay-fiber mixture sample with 7% fiber content under open curing (Figure 7(a)) and closed curing (Figure 7(b)). In addition to the curing method, time is also assumed to affect the strength of the soil and fiber mixture. The compressive strength of the undisturbed sample is 94.39 kPa. For the open-curing condition sample shown in Figure 7(a), the compressive stress increases with increasing strain until it reaches a maximum value of approximately 1509, 5131, 7434, 8719, and 8239 kPa for the samples cured for 1, 7, 14, 28, and 90 days, respectively. For the closed-condition sample, the maximum compressive strengths are 780, 996, 1132, 1303, and 1756 kPa, respectively. It can be observed that the samples left open and in equilibrium with the room conditions have much higher compressive strengths than those that are closed. These results are plotted in Figure 8 in a graph of the relationship between the time and compressive strength. The figure also shows the relationship of the weight change, i.e., the process of reducing water in the samples cured under open conditions. This decrease in water content is owing to the sample adjusting to the relative humidity of the room (ranging from 41.2%–62.4% with a temperature of 27.4–30.5 °C). As expected, the closed sample shows no change in weight, indicating that there is no change in the water content of the sample.

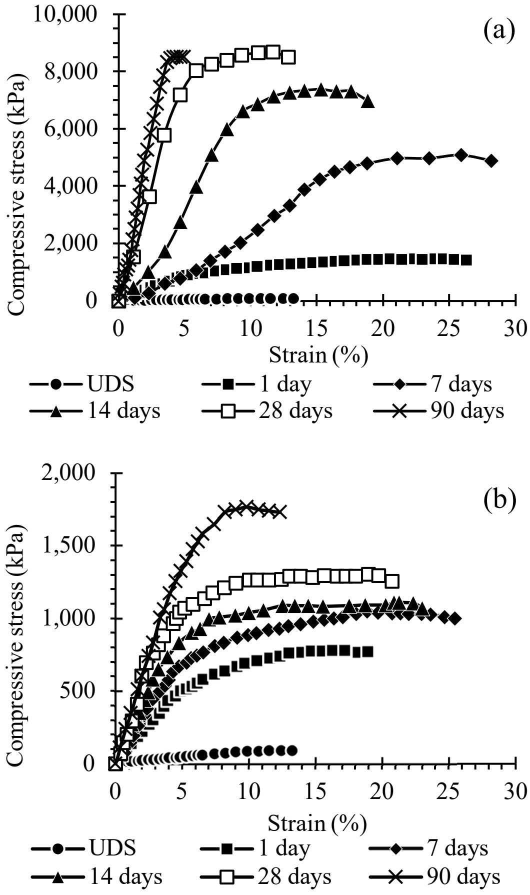

Fig. 7 Typical results of the unconfined compression test (UCT) for clay-fiber content at different curing times (a) open condition and (b) closed condition.

The decrease in the water content of the sample results in an increase in the strength of the clay owing to an increase in its negative pore water stress [38,39]. Although no direct measurements were made, suction can be calculated from the relative humidity and room temperature data. In particular, the sample is equilibrated under these conditions with a thermodynamic relationship between the suction and partial pressure of the pore water [40,41]. The negative pore water stress of the sample is in the range of 65759–122490 kPa. This increase in the negative pore water pressure causes the strength of the open sample to be much greater than that of the closed sample. At closed condition, the sample's compressive strength increases with increasing curing time, even though the water content does not change. This is consistent with the results concerning the soil-fiber friction, which increases with increasing time (Figure 6). It can be observed that this friction has a large effect on increasing the compressive strength of the sample, although the tensile strength of the fiber decreases with increasing time. This friction, together with the restrain effect, even increases the durability of the fiber-reinforced soil against freeze-thaw cycling [26]. In addition, the curing time also reduces the pore water pressure, thereby increasing the strength of the fiber-reinforced soil [42].

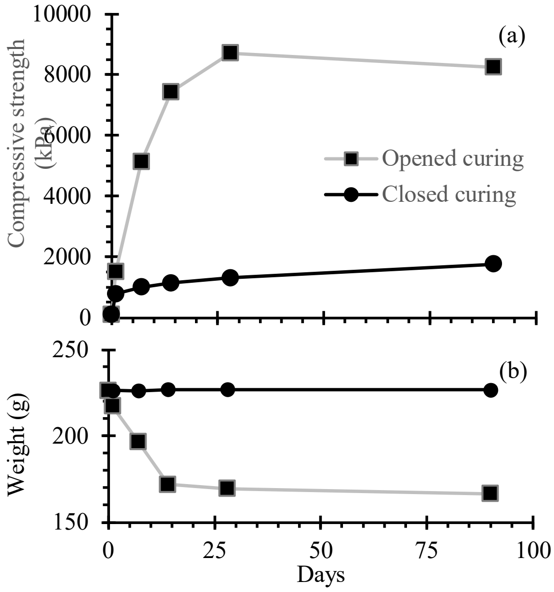

Fig. 8 Compressive strength and weight of samples as a function of time.

The increase in strength is directly proportional to the number of fibers used. Additionally, the presence of fiber creates a bridging effect on the shear plane, preventing the sample from cracking and improving its strength [43]. However, an excessive number of these results in reduced strength owing to increased friction of the fibers and reduced soil-fiber interactions [11,20]. To stabilize a soil sample using the technique proposed by Arifin et al. [11], the optimum fiber content must be determined beforehand.

Figure 9 shows the Young's modulus (E) of samples as a function of time. For samples cured in opened condition, E values are 18.31, 35.42, 72.76, 168.68, and 138.28 MPa for samples cured in 1, 7, 14, 28, and 90 days, respectively. Meanwhile, the samples that were cured at the same period of time in the opened condition had E values of 10.4, 15.42, 20.41, 24.44, and 29.30 MPa, respectively. It can be seen from the graphs and figures that the samples cured in the open condition produced higher E than those cured in the closed condition. However, the addition of fiber as a function of time has increased the E value from 10–30 times that of the E of the UDS sample (i.e., 0.96 MPa). Considering the Young's modulus [44], the addition of this fiber also resulted in an increase in sample consistency from very soft (i.e., $E<4$ MPa) to stiff in 1–7 days (i.e., $7<E<20$ MPa) and to hard after 14 days (i.e., $20<E<32$ MPa). Several researchers have also noticed this rise in the stiffness of fiber-reinforced soils [45–48]. The increase in strength and stiffness is only for samples with the addition of a 10 mm long fiber. Longer than that, both strength and stiffness tend to decrease [46,47]. Short fibers increase the possibility of crossing the slip plane, resulting in a rise in shear strength. This stiffness is also influenced by tensile strength, confining pressure, and fiber content [45].

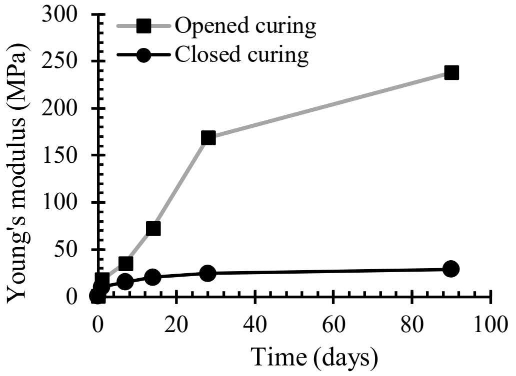

Fig. 9 Young's modulus as a function of time

4.2 Cross-Section and Longitudinal Surface of the OPEFB

Figures 10(a)–(d) show the cross-sections of the OPEFB fibers cured in dry conditions at 1, 28, 90, and 360 days. One sample was prepared for a period longer than the duration of the study (i.e., 360 days) to observe the changes in its cross-section. Figures 11(a)–(d) depict the longitudinal surfaces of the OPEFB fiber in this study after being cured for 1, 28, 90, and 360 days, respectively.

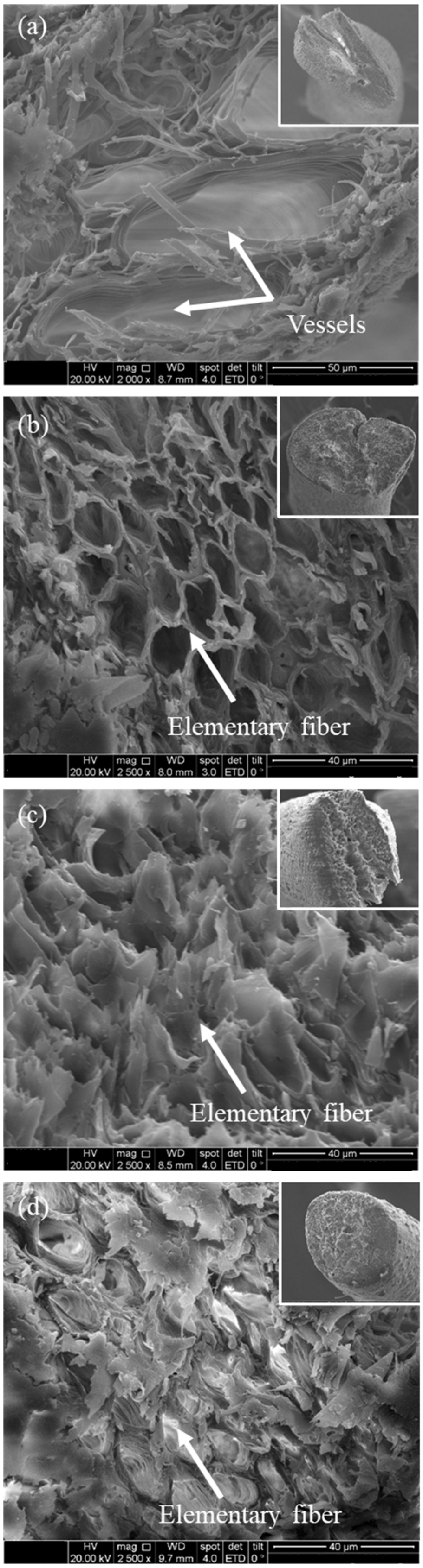

Fig. 10 Cross-section of the OPEFB (a) 1 day, (b) 28 days, (c) 90 days, and (d) 360 days.

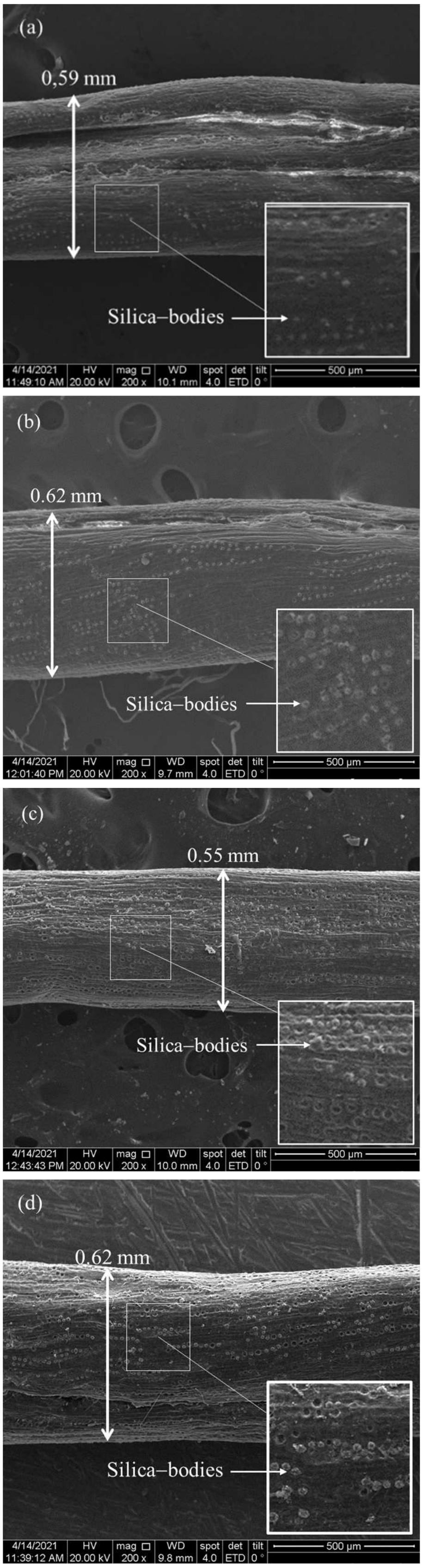

Fig. 11 Scanning electron microscopy (SEM) image of fiber surface cured in open condition for (a) 1 day, (b) 28 days, (c) 90 days, and (d) 360 days.

Figure 10(a) depicts a fresh cross-section with vessels and elementary fibers on the sidewalls. Even though the tensile strength decreases by 58% from 1 to 28 days, the elementary fiber remains clearly visible, and there is no damage at this age (Figure 10(b)). The damage is clearly visible in the fiber cross-section in the soil for 90 days, as shown in Figure 10(c).

The damage to the fiber cross-section results in a decrease in the tensile strength of the remaining fiber by almost 35 MPa, or a decrease of more than 63.78%. At 360 days, the fiber cross-section is degraded (Figure 10(d)) and based on observations, the fiber can be broken into 3–4 cm-long pieces. The longer the fiber in the soil, the more its cross-sectional structure changes.

As can be seen, the fiber diameter remains in the range being used, i.e., between 0.4–0.6 mm on average. The figures show the presence of silica bodies on the fiber surface, both in the fiber cured for 1 day (Figure 11(a)) and that cured for 360 days (Figure 11(d)). In previous studies, the silica bodies were found to play a role in the amount of friction on the surface of the OPEFB fiber [23,24,33]. In this study, there was no change in the fiber surface even though it interacted with the soil for 360 days. These results provide great hope for the use of these fibers by relying on the friction between the fiber and other materials (such as soft soil). The large difference in the fiber tensile strength and clay-fiber friction does not allow them to work together to increase the soil strength. The soil-fiber bond is released before the tensile force begins to act. However, a sufficiently high tensile force, even after curing for 90 days, will ensure that there is friction between the soil and fiber. If friction is dominant, then the important parameters in the use of this fiber will be the diameter and length of the fiber, so as to ensure the size of the surface of the fiber interacting with the soil. SEM results show that the increased strength of the fiber-stabilized soil is caused by a physical process [42].

5. CONCLUSION

This paper presents the results of research on the tensile strength and durability of OPEFB fibers used as stabilizing materials for soft clay soils under two conditions (open and closed). The results show that the tensile strength of the OPEFB fiber is approximately 98.59 MPa in the open condition and 84.92 MPa in the closed condition. These values decrease significantly with time, taking 14 days to reach 50%. The maximum tensile strength that can be safely used in the calculation for long periods of time in the soil is approximately 25% of the initial tensile strength. This study also found that soil-fiber friction plays an important role in the use of fibers for the stabilization of soft soils. This friction increases with time, particularly in the first 14 days. The results from the UCT test show an increase in compressive strength with increasing time, with a similar tendency to the soil-fiber curve.

The SEM results support the results of this study, as there is a change in the structure of the cross-section of the fiber soaked in the soil, resulting in a decrease in the tensile strength of the fiber. The SEM results on the longitudinal surface show little change; the silica bodies which affects the soil-fiber friction on the surface of the fiber remain present, even after the fiber is cured for up to 360 days.

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TENSILE STRENGTH AND DURABILITY OF OIL PALM EMPTY FRUIT BUNCH FIBER IN SOFT SOIL

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ABSTRACT: Natural fibers are already being used to stabilize soil. However, the exact mechanism by which natural fibers improve the shear strength of soil is still not clear, and it varies according to the morphology of each fiber. Its durability in soil is also an important issue in the use of natural fibers for soil stabilization. This study focused on the strength and durability of oil palm empty fruit bunch (OPEFB) fiber as a stabilizing material for soft clay. The durability was determined according to the changes in tensile strength and friction of the soil after a certain period. The clay was obtained from the village of Banyu Hirang in South Kalimantan. The fiber was obtained without treatment from the OPEFB from a palm oil processing plant. Tensile, soil–fiber friction, and unconfined compression tests were conducted for mixtures of fiber and soil. Preparations were made for each test with the same duration and conditions (1, 7, 14, 28, and 90 days) in closed and open conditions. The results showed that the average tensile strength of the fiber before use was 101 MPa. This value decreased sharply after 14 days in the soil, leaving a strength of 35.71 MPa (down by 63.78%) in the open condition and 23.89% (61.04%) in the closed condition on the 90th day. The soil-fiber friction increased with increasing time, reaching 0.15 MPa in both conditions from the initial value of 0.06 MPa. The compressive strength of the soil-fiber mixture also increased with time. The corresponding scanning electron microscope results strengthened the findings of this study.

Keywords: Tensile strength, Durability, Soft soil, Fiber, OPEFB.

1. INTRODUCTION

In addition to concrete, synthetic or natural fibers can be used for soil stabilization. The synthetic fibers presently being used include strands of waste tires [1], nylon fibers [2], polypropylene fibers [3][4,5], glass fibers [6], and basalt fibers [7]. The emerging natural fibers include coir fiber [8], wheat straw, barley straw, wood shavings [9], bamboo fiber [10], and oil palm empty fruit bunches (OPEFBs) [11,12]. In contrast to synthetic reinforcements such as geotextiles and geogrids, fiber reinforcements can be easily implanted for slope improvement and thin-layer reinforcement in field applications [13]. The inclusion of fibers is an efficient method for decreasing the cement content of collapsible soils [3]. Wu et al. [14] reported that natural fibers contribute not only to reinforcement, but also to protection against slope soil losses and riverbed erosion; they can also provide filtration or drainage for eliminating heavy metals.

Soil stabilization with fiber is influenced by many factors, including the amount of fiber [1,2,4–7,9,10,12,15,16], fiber length [5,7,10,15], moisture contents of the samples [16], fiber characteristics [6,9,12,17], fiber diameter [10], soil properties [2,17], and soil stress [1,8,17]. In some cases, natural fibers can absorb sufficient quantities of water [9] [18] [19]. This causes an increase in the fiber's moisture content, resulting in poor interface adhesion between the fiber and composite material [19]. Arifin et al. [11,20] found that a 7% OPEFB fiber absorbed water, allowing soft soil to be further compacted. Consequently, the compressive strength increased. In general, this tendency is particularly important for the stabilization of soft, high-water-content soils.

Although they have been widely studied, the interactions between soil and fiber remain very interesting for improving the geotechnical properties of soils. The shear strength of a fiber-reinforced soil comprises two components: the shear strength of the soil matrix and the tensile stress acting on the fiber [13]. In addition, the contribution of the fiber to the increase in shear strength is caused by the bonding of the soil and fiber in the pull-out mechanism as well as the tensile strength of the fiber itself [16]. These mechanisms explain the interactions between the soil and fiber in general, but other interactions may occur

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The OPEFB fiber was obtained without further treatment from a palm oil processing plant.

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between the soil and fiber, especially natural fibers. However, whether the tensile strength of the fiber or the shear of the soil matrix with the fiber is the most important part of the two mechanisms remains unknown. This means that the tensile strength and soil-fiber friction must be tested to determine how they affect the shear strength of the soil after mixing.

It is also important to test the tensile strengths of natural fibers to obtain a cheap and lightweight composite material for withstanding loads [21]. In previous studies, natural fibers such as vakka, date palm stems, and bamboo were tested and compared with other fibers such as sisal, banana stem, coconut, and oil palm. It was not explained where the palm fiber was sourced from. The order of fiber tensile strength from largest to smallest was date palm, bamboo, oil palm, coconut, vakka, sisal, and banana fiber. From reference, data on 23 natural fibers, including data on the tensile strengths of fibers such as coir (15–500 MPa), sisal (31–640 MPa), jute (29–773 MPa), and kenaf bast (18–476 ± 46 MPa) were collected and summarized by Ali [22]. The tensile strength of these fibers was very high. The tensile strength of OPEFB is reported to vary widely, even though tensile strength is a basic parameter that is directly related to other parameters. It has been reported as being in the range of 60–81 MPa [18], 74.4 MPa [23], and 21–260 MPa [24].

Besides functioning as synthetic fibers, natural fibers have the advantages of being environmentally friendly [25], locally available, able to become composites with cement or lime, inexpensive, and degradable [2][24,26]. The degradation of natural fibers is an important issue in their use as construction materials, especially in soils that tend to be moist and whose conditions can change. The fiber resistance allows for the bonds in the soil to be strengthened over time, such that when the fiber is degraded, the soil strength increases. However, there is no information on the resilience of OPEFB fibers in soils over time, so testing is required.

In addition to durability, another aspect that must be considered in the use of natural fibers is sustainability [27]. Based on data from the Directorate General of Plantations, a total of 49.71 million tons of palm oil production occurred in Indonesia in 2021 [28]. This production continues to increase annually, with an average annual increase of 9.88%. In South Kalimantan, 1.6 million tons of palm oil are produced. The remaining production, in the form of empty oil palm fruit bunches by weight, is approximately 25% of the fruit [29]. This shows the large amount of this fiber available in South Kalimantan and Indonesia.

The problem statements of this research are how much is the tensile strength of OPEFB fiber and its friction stress with soil after a certain time in the soil and by what mechanism most influences the stabilization of soft clay using fiber. This study aimed to test the strength of the OPEFB fiber (including the tensile strength), along with its friction with the soil and resistance in the soil. There was no reference for the curing time for the resistance of this fiber, so the test used a maximum of 90 days, according to the planned duration of the study. The OPEFB fiber was an untreated fiber intended to attain the starting conditions before being treated.

2. RESEARCH SIGNIFICANCE

OPEFB fiber is still relatively new in construction, especially for soil stabilization. The data obtained is expected to provide references to important components, namely the tensile strength and friction of natural fibers with the soil. The results of this study clarify the fiber contribution in the context of increasing soil strength from these two components. Besides strength, an important issue of OPEFB fiber is its resistance in the soil. After a certain time, the remaining strength of the two components provides important information on the design of the reinforcement.

3. MATERIALS AND METHODS

3.1 Materials

The materials used in this study were soft soil and OPEFBs. Clay was obtained from Jl. Governor Sarkawi, Banyu Hirang, Gambut, Banjar Regency, South Kalimantan. The clay had an initial moisture content of 56% and a specific gravity of 2.31. The liquid limit, plastic limit, and soil plasticity index (ASTM D 4318) values were 61%, 34.87%, and 26.13%, respectively. The soil contained a fine content of 95.12% and a clay content of 56.32% (ASTM D7928). According to the Unified Soil Classification System (USCS) (ASTM D2487), the soil was classified as organic clay (OH) soil.

The OPEFB was a waste product from palm oil mills at Kec. Angsana, Kab. Tanah Bumbu, South Kalimantan Province. The fiber was taken from the OPEFBs (Figure 1(a)), separated (Figure 1(b)), air-dried, and removed (Figure 1(c)). In this study, no treatment was performed on the fibers before testing. To maintain the consistency of the results, fibers were selected with diameters between 0.4–0.6 mm. A digital micrometer was used to measure the fiber diameter. The measurements were performed at three points (i.e., both ends and in the middle), and the average of the three measurements was used. This was because the natural fiber cross-section is not uniform along the length of the fiber and varies within a fiber bundle [30]. This diameter was considered when determining the stress occurring when calculating the tensile stress.

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The problem statements of this study are what mechanism most influences the stabilization of soft clay utilizing fiber and how much do the tensile strength of OPEFB fiber and its friction stress with soil change over time in the soil.

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However, it is still unclear which of the two mechanisms—the shear of the soil matrix with the fibre or the tensile strength of the fiber—is the most important.

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Fig. 1 Fiber preparation from the row material of an empty fruit bunch to the fine fiber (a) oil palm empty fruit bunch (OPEFB), (b) empty fruit bunch shredded fiber, and (c) final fiber as used.

3.2 Sample Preparation and Testing

The sample was a soil sample with added fiber, with the optimum percentage thereof obtained from previous studies [11,12]. Based on the results of previous studies, the compacted soil sample with the fiber had a dry volume weight (γ_d) of 0.92 gr/cm^3 and a moisture content of 51%. The optimum fiber content was 7%. The length of the fiber was adjusted to the diameter of the sample. For the unconfined compression test (UCT) (ASTM-D2166), a length of 10 mm was used, and for a compaction test, a length of 100 mm was used. Tensile tests were conducted on untreated samples soaked in the soil. The compaction was performed using a standard Proctor (ASTM D698), and the fibers were placed in each layer of the compaction. After compaction, the samples were placed in a layer of soil and allowed to stand for 1, 7, 14, 28, and 90 days under two conditions: an open condition (i.e., allowed to interact with the atmosphere) and a closed condition (i.e., coated with plastic wrap so that there was no change in the moisture content of the samples). These conditions indicated whether the soil was dry (above the water table) or moist (below the water table), and were expected to affect the durability of the fibers. At the specified time, the fibers were removed, cleaned, and tensile-tested. The tensile test equipment and its settings are shown in Figure 2(a).

In addition to the tensile strength, the friction between the fiber and soil is an important component in their interactions; thus, it was also tested. A mold was specially designed to perform static compaction to achieve the same density as in the UCT test (i.e., 0.92 g/cm^3 with 51% moisture content) where the fibers were not cut, as shown in Figure 2(b). The shear test was performed using the same tool as in the tensile test by modifying the bottom part, as shown in the inset of Figure 2(a).

Figure 3(a) depicts a test sample of the fiber put on a tensile apparatus. This effect is obtained if the fiber breaks at the center of the span rather than in the pinched fiber region, as illustrated in Figure 3.(b). Figure 3(c) shows the implementation of UCT on a soil sample mixed with fiber. The compressive strength taken is the compressive stress at its maximum value or at 15% strain.

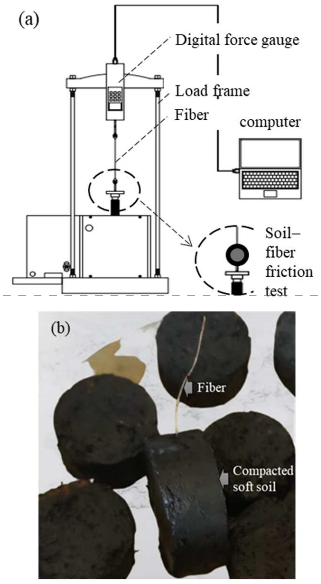

Fig. 2 Tensile and friction soil–fiber tests (a) equipment sets, and (b) soil–fiber friction samples.

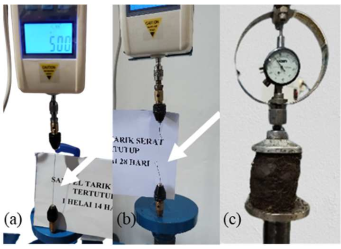

Fig. 3. (a) Pulling fiber tensile test; (b) fiber breaking; and (c) soil and fiber samples after UCT

Physically, the samples were evaluated by using scanning electron microscopy (SEM) to determine the impact of long-term fiber exposure on the tensile strength and friction between the soil and fiber. Researchers have used SEM to study the

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microscopic shapes of several natural fibers suggested as building materials ([31][18][32]).

4. RESULTS AND DISCUSSIONS

4.1 Tensile Stress of the OPEFB

Figure 4 shows typical results from the OPEFB fiber tensile test in this study. This curve is similar to that reported by Omar et al. (Omar et al., 2014a), where three regions are generated: elastic, plastic, and fracture regions. The fiber begins to be pulled into the elastic region at a strain of 0.06%–0.08%, resulting in a tensile stress of 60–70 MPa. This strain is higher than that reported by Ramlee et al. [18] (0.03%) and Omar et al. [33] (0.04%). Moreover, it continues in the plastic region until the 5%–6% strain reaches a tensile stress of 97–107 MPa (mean of 101 MPa). In addition, the tensile strength obtained in this study exceeds that reported by Ramle et al. [18] and Omar et al. [33]. The tensile strength obtained in this study is close to that reported by Danso (i.e., 110 MPa) [34] and less than that summarized by Rao and Ramakrishna (i.e., 283 MPa) [24]. The age of the parent plants, the age of the fiber after extraction, fiber surface condition (cell wall peel off, skin damage, surface treatments), gauge length, and grip pressure fluctuation during testing all contribute to this variation [24].

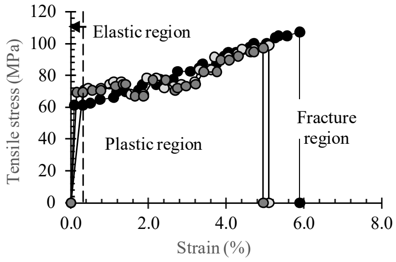

Fig. 4 Typical tensile test result.

4.1.1 Tensile strength of fiber as a function of time

Figure 5 shows the results from the tensile tests of the fibers soaked in the soil under the open and closed conditions. The values are listed in Table 1. The tensile strength decreases from 98.59 MPa on day 1 to 40.82 MPa on day 28. By 90 days, the tensile strength decreases by 5.10 to 35.71 MPa at a rate of 0.08 MPa/day.

Figure 5 also shows that the fiber in the open state has a higher tensile strength (by 10–26 MPa) than that in the closed state. The smallest difference in the 14-day cure time is approximately 6 MPa. This difference might be owing to large variations in the physical and chemical conditions of the natural fibers in the bunch even though they are taken from the same plant; this also affects their mechanical properties, including the tensile strength [30] [35]. The application conditions also affect the tensile strength, as shown in Figure 4. It is very likely that cellulose, the most influential component of the fiber tensile strength, degrades more in the closed state. In aerobic, nutrient-rich water, fibers decompose quickly, whereas previously dried fibers disintegrate more slowly [36]. In addition, the moisture affects the microorganism's development and multiplication. This is especially true for fungi, which grow quickly on cellulosic fibers when the humidity is high (approximately 80%) [37]. In general, natural fibers decompose naturally. This is advantageous when using natural fibers, as they are low in pollution. However, for long-term use, efforts must be made to maintain the strength over time. Further research is needed, especially regarding their use in soils.

Based on Table 1, the residual tensile strength after 90 days can be determined from one unit minus the percentage reduction to obtain 36.22% and 28.13% for open and closed conditions, respectively. As these numbers tend to be stable, it is safe to utilize approximately 25% of the fiber's tensile strength for calculating long-term use in the soft soil.

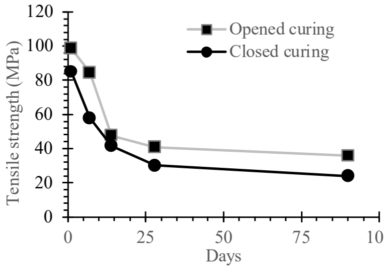

Fig. 5 Tensile strength of fiber as a function of curing time.

Table 1 Tensile strength of fiber over time with two different conditions

Time	Open curing				Closed curing			
Day	MPa	MPa	%	Rate/day	MPa	MPa	%	Rate/ day
1	98.59				84.92			
7	84.51	14.08	14.29	2.35	57.72	27.20	32.03	4.53
14	47.62	50.97	51.70	5.27	41.59	43.33	51.02	2.30
28	40.82	57.78	58.60	0.49	29.97	54.95	64.71	0.83
90	35.71	62.88	63.78	0.08	23.89	61.04	71.87	0.10

4.1.2 Soil-fiber friction as a function of time

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Figure 6 shows the friction results for the soil fibers as a function of time. As shown in the figure, the friction increases from day 1 to day 7. On day 1, both conditions produce the same friction, namely 0.06 MPa. Furthermore, in the first 7 days, the friction increases by 0.07 MPa (i.e., 111.11%) for the exposed soil, as shown in Table 2. For the closed sample, the friction increase is slightly smaller at approximately 0.05 MPa or 73.33%. A quite large increase continues to occur until day 14, with an increase of 0.01 and 0.02 MPa for the samples with open and closed conditions, respectively. The interactions between the fiber and soil can be seen in this test, especially in the first 7 days. The resulting friction is greater because large quantities of fiber are. To maintain the interactions between the soil and fiber, the amount of fiber being used is limited. Arifin et al. [11,20] found that 7% fiber on a dry-weight basis was the optimum condition for soft clay soils. Notably, the vertical compressive strength decreases as a result of the high number of fiber-to-fiber contacts.

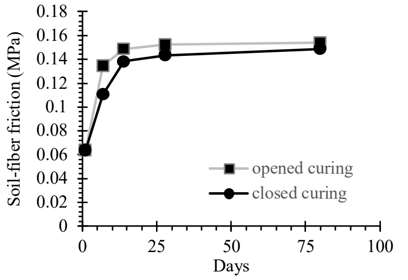

Fig. 6 Soil-fiber friction as a function of curing time.

Table 2 Soil–fiber friction as a function of time

Time	Opened curing			Closed curing		
Day	MPa	MPa	%	MPa	MPa	%
1	0.06			0.06		
7	0.13	0.07	111.11	0.11	0.05	73.33
14	0.14	0.08	133.33	0.14	0.07	116.67
28	0.15	0.09	139.00	0.14	0.08	125.00
90	0.15	0.09	141.67	0.15	0.08	133.33

4.1.3 Unconfined compressive strength of stabilized clay

Figure 7 shows the UCT results for a clay-fiber mixture sample with 7% fiber content under open curing (Figure 7(a)) and closed curing (Figure 7(b)). In addition to the curing method, time is also assumed to affect the strength of the soil and fiber mixture. The compressive strength of the undisturbed sample is 94.39 kPa. For the open-curing condition sample shown in Figure 7(a), the compressive stress increases with increasing strain until it reaches a maximum value of approximately 1509, 5131, 7434, 8719, and 8239 kPa for the samples cured for 1, 7, 14, 28, and 90 days, respectively. For the closed-condition sample, the maximum compressive strengths are 780, 996, 1132, 1303, and 1756 kPa, respectively. It can be observed that the samples left open and in equilibrium with the room conditions have much higher compressive strengths than those that are closed. These results are plotted in Figure 8 in a graph of the relationship between the time and compressive strength. The figure also shows the relationship of the weight change, i.e., the process of reducing water in the samples cured under open conditions. This decrease in water content is owing to the sample adjusting to the relative humidity of the room (ranging from 41.2%–62.4% with a temperature of 27.4–30.5 °C). As expected, the closed sample shows no change in weight, indicating that there is no change in the water content of the sample.

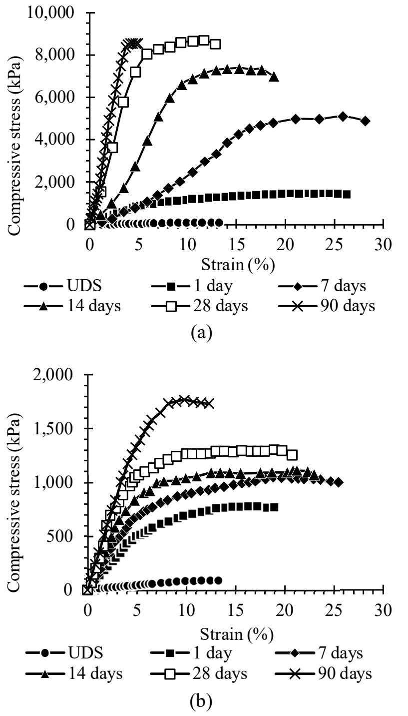

Fig. 7 Typical results of the unconfined compression test (UCT) for clay-fiber content at different curing times (a) open condition and (b) closed condition.

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The decrease in the water content of the sample results in an increase in the strength of the clay owing to an increase in its negative pore water stress [38,39]. Although no direct measurements were made, suction can be calculated from the relative humidity and room temperature data. In particular, the sample is equilibrated under these conditions with a thermodynamic relationship between the suction and partial pressure of the pore water [40,41]. The negative pore water stress of the sample is in the range of 65759–122490 kPa. This increase in the negative pore water pressure causes the strength of the open sample to be much greater than that of the closed sample. At closed condition, the sample's compressive strength increases with increasing curing time, even though the water content does not change. This is consistent with the results concerning the soil-fiber friction, which increases with increasing time (Figure 6). It can be observed that this friction has a large effect on increasing the compressive strength of the sample, although the tensile strength of the fiber decreases with increasing time. This friction, together with the restrain effect, even increases the durability of the fiber-reinforced soil against freeze-thaw cycling [26]. In addition, the curing time also reduces the pore water pressure, thereby increasing the strength of the fiber-reinforced soil [42].

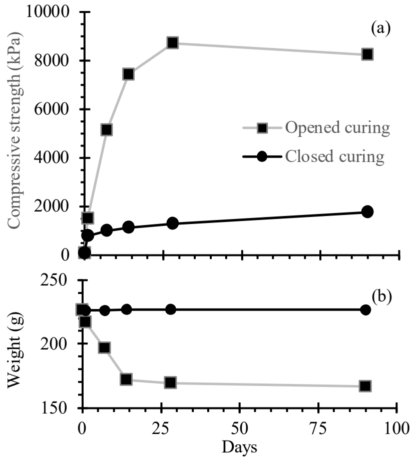

Fig. 8 Compressive strength and weight of samples as a function of time.

The increase in strength is directly proportional to the number of fibers used. Additionally, the presence of fiber creates a bridging effect on the shear plane, preventing the sample from cracking and improving its strength [43]. However, an excessive number of these results in reduced strength owing to increased friction of the fibers and reduced soil-fiber interactions [11,20]. To stabilize a soil sample using the technique proposed by Arifin et al. [11], the optimum fiber content must be determined beforehand.

Figure 9 shows the Young's modulus (E) of samples, as a function of time. For samples cured in opened condition, E values are 18.31, 35.42, 72.76, 168.68, and 138.28 MPa for samples cured in 1, 7, 14, 28, and 90 days, respectively. Meanwhile, the samples that were cured at the same period of time in the opened condition had E values of 10.4, 15.42, 20.41, 24.44, and 29.30 MPa, respectively. It can be seen from the graphs and figures that the samples cured in the open condition produced higher E than those cured in the closed condition. However, the addition of fiber as a function of time has increased the E value from 10–30 times that of the E of the UDS sample (i.e., 0.96 MPa). Considering the Young's modulus [44], the addition of this fiber also resulted in an increase in sample consistency from very soft (i.e., E<4 MPa) to stiff in 1–7 days (i.e., 7<E<20 MPa) and to hard after 14 days (i.e., 20<E<32 MPa). Several researchers have also noticed this rise in the stiffness of fiber-reinforced soils [45–48]. The increase in strength and stiffness is only for samples with the addition of a 10 mm long fiber. Longer than that, both strength and stiffness tend to decrease [46][47], Short fibers increase the possibility of crossing the slip plane, resulting in a rise in shear strength. This stiffness is also influenced by tensile strength, confining pressure, and fiber content [45].

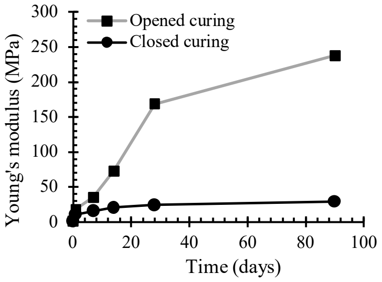

Fig. 9 Young's modulus as a function of time

4.2 Cross-Section and Longitudinal Surface of the OPEFB

Figures 10(a)–(d) show the cross-sections of the OPEFB fibers cured in dry conditions at 1, 28, 90, and 360 days. One sample was prepared for a period longer than the duration of the study (i.e., 360 days) to observe the changes in its cross-section. Figure 10(a) depicts a fresh cross-section with vessels and

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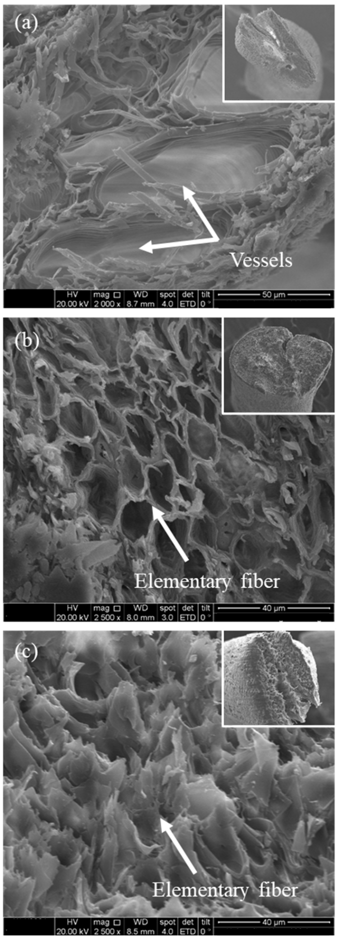
elementary fibers on the sidewalls. Even though the tensile strength decreases by 58% from 1 to 28 days, the elementary fiber remains clearly visible, and there is no damage at this age (Figure 10(b)). The damage is clearly visible in the fiber cross-section in the soil for 90 days, as shown in Figure 10(c).



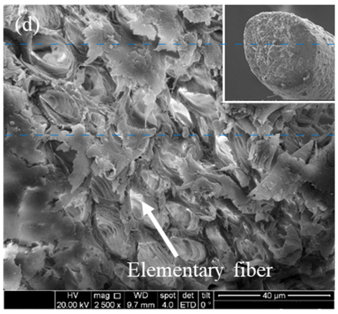


Fig. 10 Cross-section of the OPEFB (a) 1 day, (b) 28 days, (c) 90 days, and (d) 360 days.

The damage to the fiber cross-section results in a decrease in the tensile strength of the remaining fiber by almost 35 MPa, or a decrease of more than 63.78%. At 360 days, the fiber cross-section is degraded (Figure 10(d)) and based on observations, the fiber can be broken into 3–4 cm-long pieces. The longer the fiber in the soil, the more its cross-sectional structure changes.

Figures 11(a)–(d) depict the longitudinal surfaces of the OPEFB fiber in this study after being cured for 1, 28, 90, and 360 days, respectively. As can be seen, the fiber diameter remains in the range being used, i.e., between 0.4–0.6 mm on average. The figures show the presence of silica bodies on the fiber surface, both in the fiber cured for 1 day (Figure 11(a)) and that cured for 360 days (Figure 11(d)). In previous studies, the silica bodies were found to play a role in the amount of friction on the surface of the OPEFB fiber [23,24,33]. In this study, there was no change in the fiber surface even though it interacted with the soil for 360 days. These results provide great hope for the use of these fibers by relying on the friction between the fiber and other materials (such as soft soil). The large difference in the fiber tensile strength and clay-fiber friction does not allow them to work together to increase the soil strength. The soil-fiber bond is released before the tensile force begins to act. However, a sufficiently high tensile force, even after curing for 90 days, will ensure that there is friction between the soil and fiber. If friction is dominant, then the important parameters in the use of this fiber will be the diameter and length of the fiber, so as to ensure the size of the surface of the fiber interacting with the soil. SEM results show that the increased strength of the fiber-stabilized soil is caused by a physical process [42].

5. CONCLUSION

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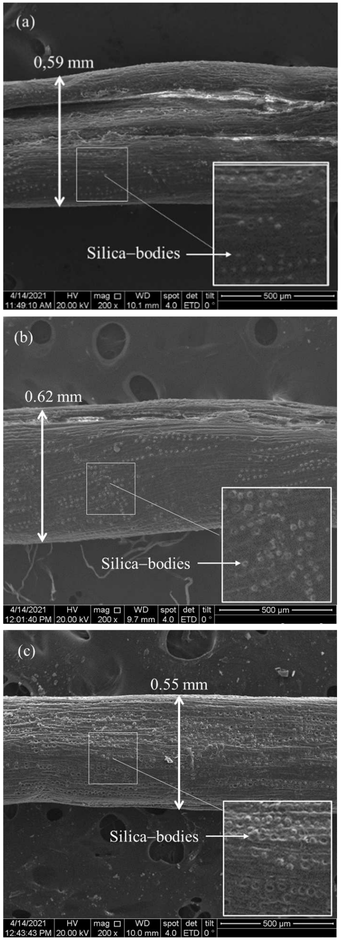
This paper presents the results of research on the tensile strength and durability of OPEFB fibers used as stabilizing materials for soft clay soils under two conditions (open and closed). The results show that the tensile strength of the OPEFB fiber is approximately 98.59 MPa in the open condition and 84.92 MPa in the closed condition. These values decrease significantly with time, taking 14 days to reach 50%. The maximum tensile strength that can be safely used in the calculation for long periods of time in the soil is approximately 25% of the initial tensile strength. This study also found that soil-fiber friction plays an important role in the use of fibers for the stabilization of soft soils. This friction increases with time, particularly in the first 14 days. The results from the UCT test show an increase in compressive strength with increasing time, with a similar tendency to the soil-fiber curve.



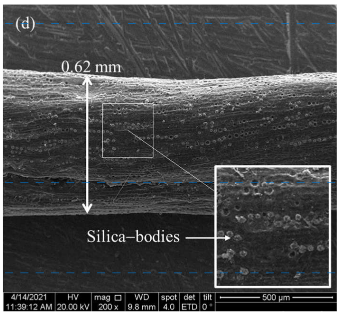


Fig. 11 Scanning electron microscopy (SEM) image of fiber surface cured in open condition for (a) 1 day, (b) 28 days, (c) 90 days, and (d) 360 days.

The SEM results support the results of this study, as there is a change in the structure of the cross-section of the fiber soaked in the soil, resulting in a decrease in the tensile strength of the fiber. The SEM results on the longitudinal surface show little change; the silica bodies which affects the soil-fiber friction on the surface of the fiber remain present, even after the fiber is cured for up to 360 days.

6. ACKNOWLEDGMENTS

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Rudi Siswanto: Methodology, Design and manufacture of Equipment
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