

MECHANICAL PROPERTIES AND MORPHOLOGICAL STRUCTURES OF ALKALINE TREATED BAMBOO AND COCONUT FIBERS FOR NATURAL GEOTEXTILE APPLICATION

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ABSTRACT: Synthetic geotextiles are known for their wide range of applications in geotechnical engineering, especially for erosion control and slope stability. However, these materials are environmentally concerning due to their lack of biodegradability and are made of petroleum-based polymers. Hence, these materials can create environmental problems and have long-term ecological impacts. The objective is to (1) explore the mechanical properties and morphological properties of indigenous natural fibers (bamboo, coconut) and (2) to determine whether blended bamboo-coconut (BAMCO) fibers can replace synthetic fibers. The fibers were soaked in a 6% sodium hydroxide (NaOH) solution for 24 hours. Tensile strength of single fibers and twines and ropes was assessed using ASTM D3822 and ASTM D2256, respectively. Surface morphology was characterized by scanning electron microscopy (SEM), and cellulose content was quantified by Fourier transform infrared spectroscopy (FTIR), which explains the change in tensile strength. In the experimental results, the tensile strength of untreated bamboo fibers was higher (12.4375 MPa) than that of coconut fibers (1.84457 MPa). The tested properties indicate that tensile strength is enhanced by alkaline treatment in bamboo and coconut fibers, with values of 26.9175 MPa and 2.03689 MPa, respectively. This increased tensile strength is attributed to greater exposure of cellulose and the thicker fiber morphology. Furthermore, the load-carrying capacity also improved in composite bamboo-coconut or BAMCO rope made of the combined twines of single fibers. This study showed that natural fibers from bamboo and coconut, particularly the BAMCO geotextile, can be potential natural geotextiles.

Keywords: Coconut Fiber, Bamboo Fiber, Morphological Structure, Natural Geotextile, Synthetic

1. INTRODUCTION

In geotechnical engineering, enhancing soil stability and strength through fiber reinforcement is of considerable interest. Natural or synthetic fiber reinforcement of the soil improves the stability of earth-retaining structures, especially in slopes, dams, and embankments [1]. Additionally, geosynthetic reinforcement is crucial in construction projects because it enhances soil stability and increases its load-bearing capacity [2]. Geosynthetics have therefore become versatile engineering materials widely used in geotechnical, environmental, hydraulic, transportation, and many other private-sector infrastructure applications [3]. One type of geosynthetic material is geotextiles, which have been widely used for numerous geotechnical applications, including soil erosion control, slope stability, and soil reinforcement. In 2022, the geotextile industry generated \$7.10 billion worldwide, with a yearly growth prediction of 6.6% between 2023 and 2030 [4]. Geotextiles are permeable fabrics made from woven and non-woven materials. These can either be synthetic fibers or natural fibers. A study noted that geotextiles have various uses in geotechnical applications, including filtration, separation, reinforcement, drainage, and erosion control [5]. Synthetic geotextiles have demonstrated versatility, which is why they have been preferred over the years

[6]. Geotextiles are typically made from synthetic materials, such as polymers (polypropylene, polyester, polyethylene, and polyamides) [7]. Petroleum-based polymers were used in the manufacturing of geotextiles due to their high tensile strength and high degradation resistance [8]. Accordingly, they are non-degradable materials and can lead to long-term environmental pollution [9]. Prior studies reinforce this idea, demonstrating that environmental deterioration and microplastic contamination occur due to the incorporation of polymer-based geotextiles, especially along coasts [10-11]. The environmental impact of synthetic materials stems from their inability to break down and their reliance on polymers in production. This raises the need for environmentally friendly construction materials. Hence, this study was conducted.

Natural geotextiles, as a growing trend, are sustainable. They are derived from fibrous plants, including jute, coconut coir, sisal, and bamboo. They are biodegradable, locally sourced, and economically viable [12]. Previous research has investigated raw geotextiles from vegetables and other renewable sources. Accordingly, they have several advantages, as they naturally break down, are less carbon-intensive, and contribute to the local economy [13]. As explained, studies show that natural fibers perform similarly to synthetics in a range of short to medium-scale environmental applications, in particular

erosion control and slope protection [14]. These include jute and coir geotextiles, which have been effectively used in temporary erosion control and revegetation projects where biodegradability is a synergism with natural land restoration [15]. A study on pineapple and coconut fibers called PICONET geotextile offers an effective balance of tensile strength and flexibility, making it suitable for mitigating soil erosion along road embankment slopes [16]. Chemical and mechanical properties of abaca and pineapple leaf fibers were also studied [17].

On the other hand, chemical treatment of fibers has emerged as a recent innovation to enhance the mechanical properties of natural geotextiles. A previous study described the use of sodium hydroxide (NaOH) as an alkaline treatment of fibers [18]. To improve strength and flexibility, a study was conducted on a combination of natural fibers (banana and coir) [19]. Although these materials are often challenging for long-term performance in high-moisture environments, their adoption is on the rise due to their eco-friendliness and economic advantages. And even more so from environments where natural resources are favored by environmental regulations, such as with biodegradable construction materials [20]. It has been found that the flexibility and versatility of bamboo fibers are important factors in their industrial application as an essential production material for ropes and woven fabrics [7]. Cellulose, hemicellulose, and lignin are the main constituents of bamboo, although small quantities of aqueous extract, pectin, and inorganic substances are present [21]. We pay particular attention to the selected bamboo types, as their chemical composition can vary. As regards bamboo timbers, the main constituents are 60% to 70% cellulose, 20% to 25% pentosans, 20% to 30% hemicelluloses, and 20% to 30% lignin [22].

Conversely, coconut fiber is friction-resistant, water-resistant, and does not break easily, rot, nor can it be inhabited by termites. Coconut fibers are produced from the shell and are considered inexpensive, economical, and common materials on the market. It increases mechanical properties such as shear strength, tensile strength, and bearing capacity, depending on the fiber proportion and size [23]. It increases mechanical properties like shear strength, tensile strength, and bearing capacity based on the proportion and the size of the fiber [23]. Under the Department of Public Works and Highways (DPWH) Department Order (DO) No. 142, Series of 2016, COCONET - coconut fiber twine, which can be spun manually or by machine, is woven into blankets that come in various densities and in various dimensions. COCONET is one of the most well-known geotextile materials in the Philippines. Due to its longevity, it is recommended for slope protection, erosion protection, and erosion control. A study was conducted to evaluate the use of bamboo fiber as an engineered soil

erosion-resistant geotextile for soil loss treatment on erosion-prone sites [24]. According to their findings, bamboo used as a natural woven geotextile outperformed the site's existing coir geotextiles as an eco-hydrological tool for protecting steep slopes from erosion, while retaining the coir for erosion protection. This study intended to examine the engineering potential of fibers for natural geotextiles in the context of small-to-medium-scale geotechnical applications, especially where temporary reinforcement, erosion control, and sustainability are primary design considerations rather than long-term durability. The current study investigated the mechanical properties and comparative properties of bamboo and coconut natural fibers and their twines. It looked into developing a blended rope made from bamboo-coconut coir called BAMCO rope. The tensile strength of BAMCO rope was analyzed, and its acceptance as a raw material for woven natural geotextile was determined.



Fig. 1 Coconut and bamboo fibers

The subsequent sections are: research significance which explains the importance of the current study and the gap it aims to address; the materials and methods which presents the materials used and the procedures followed; the results and discussion present the study's findings and interpret their meaning in relation to existing knowledge; and the conclusion which summarizes the major outcomes, highlights their overall relevance, and offers recommendations for future work.

2. RESEARCH SIGNIFICANCE

Several studies were conducted to independently explore natural fibers for geotextile applications. These studies lacked blended rope mechanical data, and there are limited SEM or FTIR correlations with tensile behavior. Moreover, no research has investigated the combination of bamboo and coconut fibers to create a natural geotextile as a substitute for synthetics. Although bamboo and coconut fibers are abundant raw materials, they remain underused in engineering. In this study, the potential of blended bamboo and coconut fibers as natural geotextile materials was investigated, thus promoting

environmental conservation and circular economies through agricultural byproducts utilization.

3. MATERIALS AND METHODS

3.1 Materials and Sources

Bamboo and coconut fibers were utilized as raw materials in this study. The researchers collected mature bamboo culms in Barangay Simbalan, Buenavista, Agusan del Norte, to obtain bamboo fibers. A study reported that bamboo grown for 2–3 years had ideal fibers because its cell walls are fully thickened, and the material contains a high cellulose-to-lignin ratio [25]. Bamboo fibers were collected using a local decorticator machine. After extraction, the bamboo fibers were air-dried and packaged in cellophane bags. It reduced the likelihood that contaminants would affect the fibers, thereby minimizing changes in their characteristics during the tests. The dry fibers were taken to Malingao Community Service Multipurpose Cooperative (MCOCO) in Tubod, Lanao del Norte, for twining and roping. The coconut fibers were also sourced from MCOCO. DPWH has named MCOCO as one of the suppliers of coconet materials for slope protection. The sodium hydroxide (NaOH) solution used during chemical treatment was obtained from a chemical supplier in La Victoria, Cagon, Cagayan de Oro City.

3.2 Preparation of Twine and Rope

The twine diameters of specimens were presented in Table 1. These twisted fibers made with bamboo, shown in Fig. 2, were spun by hand and produced twines with a diameter of approximately 5.0 ± 1.0 mm. The same procedure and target diameter were observed in producing the coconut twine from coconut fibers, as shown in Fig. 3. That twine diameter for Item 622 - Coconet Bio-Engineering Technology was acceptable for the DPWH Standard Specification [26].

Table 1. Diameter of the specimens

Specimen	Diameter (mm)
Twine (Untreated and Treated)	
Bamboo	$5.0 \text{ mm} \pm 1.0 \text{ mm}$
Coconut	$5.0 \text{ mm} \pm 1.0 \text{ mm}$
Rope (Untreated and Treated)	
BAMCO Rope (50:50 bamboo-coconut)	$10.0 \text{ mm} \pm 1.0 \text{ mm}$

Individual bamboo and coconut twines were mixed in a 50:50 ratio to produce a composite rope known as a BAMCO rope with the target diameter of approximately 10.0 ± 1.0 mm, as shown in Fig. 4.

Thickness in this case was in accordance with the thickness standard set by DPWH for coconets.



Fig 2 Bamboo twine



Fig. 3 Coconut twine



Fig. 4 Bamboo-coconut (BAMCO) rope

3.3 Alkaline Treatment of Specimens

The treatment was conducted to improve the mechanical and morphological characteristics of the

specimens. The fibers were chemically treated in a 6% NaOH solution (alkaline treatment agent) as described in a previous study [18]. A 600 mL NaOH solution was added to 5 liters of distilled water. The samples were then fully submerged in the solution and maintained under immersion for 24 hours. The specimens were washed, and fresh water was used to rinse the samples. The samples were then air-dried for 24 hours following treatment. This was done to minimize excess moisture, which could negatively affect the mechanical behavior of the samples during testing. Fig. 5 shows the bamboo fiber and NaOH solution used for treatment. Fig. 6 shows the coconut fiber to be treated with and NaOH solution.



Fig. 5 Alkaline solution and bamboo fiber



Fig. 6 Alkaline solution and coconut fiber

3.4 Laboratory Testing of the Untreated and Treated Fibers

3.4.1 Tensile Strength Test (ASTM D3822)

A Universal Testing Machine (Shimadzu AGS-X Series) at a test speed of 5 mm/min, as shown in Fig. 7, was used to determine the fibers' tensile strength according to ASTM D3822 [27]. The test was performed on a representative amount of both untreated and treated bamboo and coconut fibers. Equation 1 was used to calculate the tensile strength of the fiber employed in the specified loadings.

$$\sigma = \frac{F_{max}}{A_0} \quad (1)$$

where σ = tensile strength in MPa; F_{max} = maximum load in N; A_0 = original cross-sectional area.



Fig. 7 Tensile strength testing machine

3.4.2 Scanning Electron Microscopy (SEM)

Morphological structures of the untreated and treated fibers were determined with a x2000-magnified Scanning Electron Microscope (JEOL) (JSM-IT200). This method was conducted in Mindanao State University-Iligan Institute of Technology (MSU-IIT), Iligan City. The specimens were sputter-coated with a thin layer of gold to enhance conductivity and reduce charging [28]. High-resolution images were produced through a specific analysis to understand the fiber's morphological configuration and tensile strength.

3.4.3 Fourier Transform Infrared Spectroscopy

The cellulose content of the untreated and treated specimens was assessed by using Fourier Transform Infrared Spectroscopy (Shimadzu IRTracer 100). The test was performed at Mindanao State University-Iligan Institute of Technology (MSU-IIT) in Iligan City. The test shows the effects of cellulose exposure on the different tensile strengths as well as the effects of the alkaline treatment.

3.5 Laboratory Testing of the Untreated and Treated Twines and Ropes

3.5.1 Tensile strength test (ASTM D2256)

The tensile strength of the twines and ropes was determined by using a Universal Testing Machine (Shimadzu AGS-X Series) at a test speed of 5 mm/min, following the ASTM D2256 [29]. The tensile strength of the twines and ropes was evaluated using Equation 2 to determine the tensile strength under loading conditions.

$$T = \frac{F_{max}}{A} \quad (2)$$

where T = tensile strength in MPa; F_{max} = maximum force applied before the material breaks, (N); A = cross-sectional area of the yarn in mm^2 .

3.6 Statistical Analysis

A one-way analysis of variance (ANOVA) was conducted to compare the tensile strength of untreated fibers and alkaline-treated fibers. The dataset was examined for normality and homogeneity of variance before analysis. The ANOVA assessed whether alkaline treatment produced a significant difference in mean tensile strength compared to the untreated condition

4. RESULTS AND DISCUSSION

4.1 Tensile Strength of the Untreated Fibers

Tensile strength of untreated and treated bamboo and coconut fibers is presented in Table 2. The tensile strength of bamboo fiber was higher than coconut fiber. The untreated bamboo fiber exhibits 5.74 times higher tensile strength with 12.4375 MPa than the untreated coconut coir fiber with 1.84457 MPa. The superior tensile strength is attributed to better microstructural and chemical properties of bamboo fiber. The difference lies in the higher cellulose content in bamboo than in coconut fiber (at 3376 cm^{-1} and 3335 cm^{-1}), among other factors. Cellulose is recognized as a principal load-bearing material in natural fibers. Cellulose, which is a highly crystalline and oriented polymer, enhances tensile strength due to improved intermolecular adhesion and increased stiffness in the fibers. This molecular arrangement enables natural fibers to resist strain and deform under load, thereby elevating their strength and improving the overall flexibility of their mechanical response. Coir fibers, on the other hand, include a much higher proportion of lignin [30] [13]. This lignin content contributes to increased brittleness, as its amorphous and cross-linked structure limits molecular mobility within the fiber. As a result, higher lignin levels tend to reduce the tensile capacity of the material, making the fibers less flexible and more prone to fracture under load, even though it is beneficial in terms of rigidity and decay resistance.

In addition, bamboo fibers have a more aligned and denser structure, enabling optimal stress distribution along the fiber axis. However, coir has advantages of being tough, elastic, and biodegradable, but it has reduced tensile strength, and thus it can be used in short-term geotextile applications like erosion control due to its high flexibility and toughness [14-15]. Due to its mechanical properties, bamboo's structural and compositional properties make it better

suitable to higher mechanical performance in such applications

4.2 Tensile Strength of the Treated Fibers

The tensile strength of treated bamboo and coconut fibers is presented in Table 2. Due to the higher cellulose content in treated bamboo compared to treated coconut fiber, treated bamboo has shown higher tensile strength. The cellulose content for untreated and treated bamboo fibers is 3376 cm^{-1} and 3382 cm^{-1} (wavenumber), respectively. The cellulose of untreated and treated coconut fibers is 3335 cm^{-1} and 3339 cm^{-1} (wavenumber), respectively. This means that the alkaline treatment significantly influences the mechanical properties of the fibers.

Fig. 8 shows the fiber breakage after the tensile strength test. The comparison of the effect of alkaline treatment on the tensile strength of the two fibers is also shown in Fig. 9. The tensile strength of the untreated to treated bamboo fiber has increased significantly from 12.4375 MPa to 26.9175 MPa, marking an increase of approximately 1.16 times after treatment with an alkaline solution. The same applies to coconut fiber, which increases from 1.84457 MPa to 2.03689 MPa, a 10.43% increase after treatment. Alkaline treatment enhances the tensile strength of natural fibers through chemically modifying their external and internal properties. NaOH removes lignin, hemicellulose, waxes, and other impurities from the fiber surface [31].



Fig. 8 Fibers after the tensile strength testing

Table 2. Tensile strength of the untreated and treated fibers

Fiber	Thickness (mm)	Width (mm)	Gauge Length (mm)	Maximum Force (N)	Tensile Strength (MPa)
Untreated Bamboo	1	1	100	12.4375	12.4375
Untreated Coconut	1	1	100	1.84457	1.84457
Treated Bamboo	1	1	100	26.9175	26.9175
Treated Coconut	1	1	100	2.03689	2.03689

Table 3. Tensile strength of the untreated twines

Untreated Twines	Thickness (mm)	Width (mm)	Gauge Length (mm)	Maximum Force (N)	Tensile Strength (MPa)
Bamboo Twine	5.55	5.91	100	174.32	5.31
Coconut Twine	5.82	8.17	100	152.05	3.20

Table 4. Tensile Strength of the Treated Twine

Treated Twines	Thickness (mm)	Width (mm)	Gauge Length (mm)	Maximum Force (N)	Tensile Strength (MPa)
Bamboo Twine	5.51	5.91	100	182.97	5.62
Coconut Twine	4.98	7.15	100	158.49	4.45

Table 5. Tensile strength of the untreated and treated BAMCO ropes

Ropes	Thickness (mm)	Width (mm)	Gauge Length (mm)	Maximum Force (N)	Tensile Strength (MPa)
Untreated BAMCO Rope	9.65	11.2	100	198.04	1.83
Treated BAMCO Rope	10.65	10.20	100	258.21	2.38

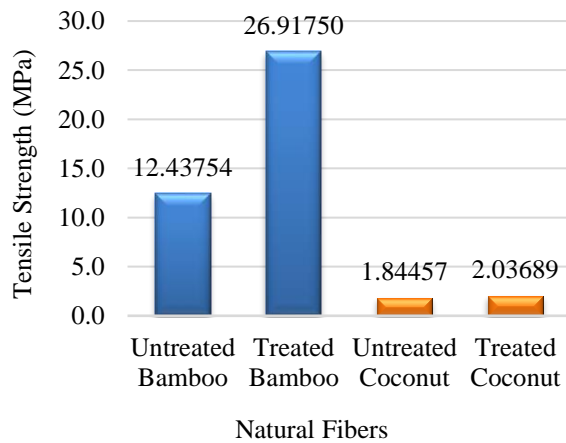


Fig. 9 Tensile strength of the natural fibers

Table 6. Fiber's properties

Fiber	Tensile strength, MPa	Maximum strain in tension	Elastic modulus, MPa
UBF	12.44	0.0709	175.305
TBF	26.92	0.0363	741.243
UCF	1.84	0.0108	170.163
TCF	2.04	0.1335	15.259

In Table 6, the UBF stands for untreated bamboo fiber, TBF is treated bamboo fiber, UCF is untreated coconut fiber, and TCF is treated coconut fiber.

The non-structural elements (lignin, hemicellulose, waxes, and other impurities) contribute to the amorphous portions of the fiber, and thus, it is not very durable. The elimination of impurities increases the relative proportion of cellulose as the primary load-bearing component, leading to better molecular conformations and stronger hydrogen bonding in the fiber structures [32]. Moreover, alkali treatment causes fibrillation, revealing finer fibrils on the fiber surface and thereby improving surface roughness. This provides enhanced inter-fiber bonding and improved stress transfer [30]. This modification of the surface adds to more mechanical interlock for composites. The treatment may also induce a more organized crystalline structure of cellulose, enhancing the fiber's tensile strength [33]. But under the right conditions, the treatment works; if it is too aggressive, it damages the fibers, and their mechanical properties will also drop. The stress-strain relationships are presented in Fig. 10 and Fig. 11, showing higher tensile strength for treated fibers. Bamboo fibers are strong but brittle, while coconut fibers are weaker but more flexible.

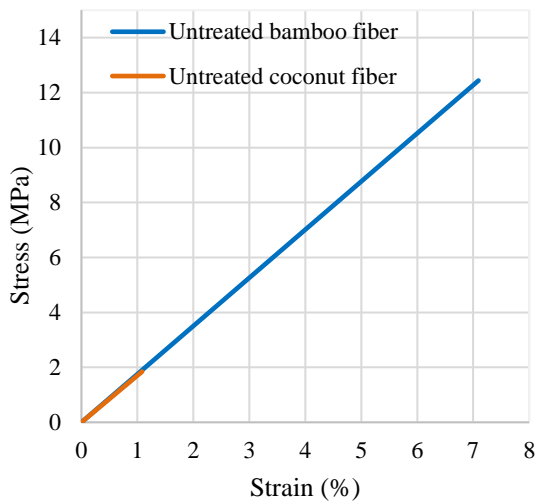


Fig. 10 Stress-strain relationship of the untreated fibers

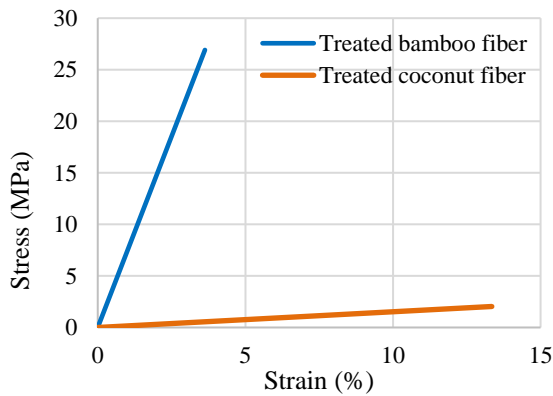


Fig. 11 Stress-strain relationship of the treated fibers

4.3 Tensile Strength of the Untreated Twines

Table 3 showed that the tensile strength of bamboo twine and coconut twine was significantly lower than that of individual bamboo fibers, as shown in Table 2. It can be said that there is a reduction in tensile strength. In bamboo, the microstructure is highly aligned, which promotes adequate load transfer along the fiber axis. However, twining disrupts individual fibers from aligning in an equally good manner. Since there are voids and the potential for inter-fiber slip in this twine, local stress levels increase as well. It is this uneven distribution that produces concentrated, localized stresses and early points of failure under tensile stress, as described [30]. Twisting introduces torsional and residual strains into the fiber assembly, and these added stresses can weaken the material's overall mechanical properties. Not optimizing the twist angle leads to internal friction and will decrease the bond strength of the fiber, resulting in a reduction of the tensile strength [33]. As such, this provides an explanation for the

observed decline in tensile strength when bamboo fibers are bundled and twisted into twine. Thus, proper alignment using mechanical or manual alignment tools, by placing fibers parallel to each other before twisting, may help address misaligned fibers, which is one of the largest causes of a decrease in tensile strength. Aligned fibers improve stress transfer and reduce weak points along the twine [33].

Table 3 shows that the untreated bamboo twine has a tensile strength of 5.31 MPa, which is 65.94% higher than the untreated coconut twine, which has a tensile strength of 3.20 MPa. The intrinsic characteristics of bamboo fibers, which possess a higher cellulose content compared to coir, are the major reason for the superior tensile strength of bamboo twine. Bamboo fibers exhibit a more aligned and compact microstructure, which promotes better stress distribution as well as mechanical resistance to fracture.

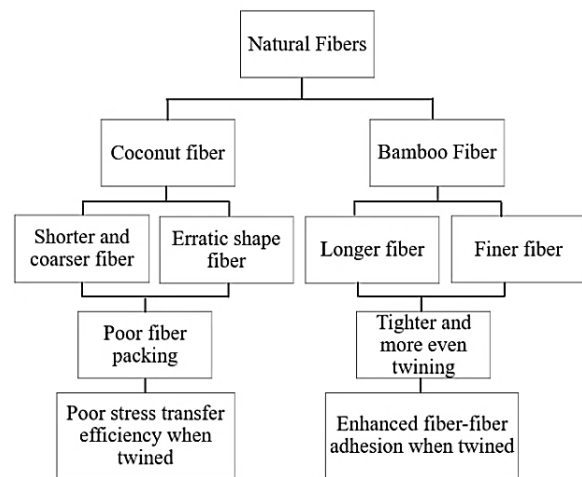


Fig. 12 Bamboo and coconut fibers when twined

The crystallinity index of bamboo is also higher, indicative of a better hierarchical inter-chain organization of cellulose and a higher tensile strength [31]. Coconut and bamboo fibers differ in shape and texture, leading to variable behavior during twining. The comparison of bamboo and coconut fiber is presented in Fig. 12, as described in the previous study [34]. While bamboo fiber is longer and finer, coir is shorter and coarser, leading to higher voids and lower bond strength when twining, and thus diminished strength [34].

4.4 Tensile Strength of the Treated Twines

Table 4 shows the tensile strength of treated bamboo and coconut twines. It shows a further increase in tensile strength for both twines after alkaline treatment. The table shows that the treated bamboo twine has a tensile strength of 5.62 MPa,

which is 26.29% higher than the treated coconut twine, which has a tensile strength of 4.45 MPa. This mechanical behavior is attributed to differences in cellulose content between the two fibers.

Fig. 13 shows the comparison of the tensile strength between the untreated and treated twines. The experimental results demonstrated that the tensile strength of the treated twines was significantly higher than that of the untreated counterparts. The untreated bamboo twine has a tensile strength of 5.31 MPa, increasing it to 5.62 MPa for the treated one, representing a 5.84% increase. On the other hand, the untreated coconut twine has a tensile strength of 3.20 MPa, which increases to 4.45 MPa for the treated twine, representing a 39.06% increase in the fiber. The enhancement of the tensile strength of the fiber was attributed to the chemical treatment with NaOH, which modified the surface of the fiber to increase the adhesion between fibers. Non-cellulosic matter, such as lignin, hemicellulose, waxes, and surface impurities (which affect the successful transfer of stresses), can be eliminated by the alkaline approach [35].

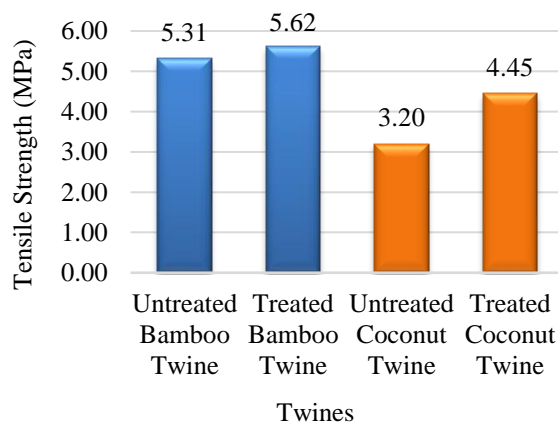


Fig. 13 Tensile strength of the untreated and treated twines

Thus, the fibers treated contain more cellulose, the most important structural polymer for tensile strength due to its high crystallinity and molecular alignment [30-31]. In addition, the NaOH treatment led to fibrillation, allowing the observation of finer fibrils and increased surface roughness. This improved mechanical bonding reduced the gaps between the fibers during loading, thus stress was shared across the load. Hydroxyl groups were found to be present and gave more hydrogen bonding strength between neighboring fibers [32]. This collectively helped with the formation of the twine that is more bonded and tougher with better tensile strength. It is crucial, however, that the handling aspects, including NaOH concentration and fiber soaking time, be tailored to

avoid fiber degradation, as greater exposure results in decreased cellulose integrity and mechanical strength [33-34].

4.5 Tensile Strength of the Untreated and Treated Ropes

Table 5 shows the tensile strength of untreated and treated composite bamboo-coconut (BAMCO) ropes. The treated bamboo-coconut (BAMCO) composite rope exhibited a significantly higher tensile strength of 2.38 MPa than its untreated counterpart (1.83 MPa), a 30.05% increase due to treatment. This result indicates a positive effect of alkaline treatment and fiber blending, as it improves mechanical performance, as evidenced by the significant increase in tensile strength after treatment. The improvement is achieved by combining modifications to the fiber surface with the synergistic effects of bamboo and coconut fibers. Prior work has demonstrated that the alkaline treatment improves fiber–fiber adhesion by extracting surface impurities, including lignin, hemicellulose, and waxes, thereby increasing the relative cellulose content and enabling better mechanical interlocking of fibers [30–31]. Although the BAMCO rope carries a higher maximum load (force), the applied load is distributed over a much larger area. As a result, the calculated tensile strength of the rope is lower than that of the twines, which have a smaller cross-sectional area. The fiber misalignment or inter-fiber slippage, if addressed, can enhance the efficiency of stress transfer and consequently the tensile strength.

A previous study mentioned that the integration of two distinct natural fibers into a composite yarn structure improved stress distribution along the length of the rope. Bamboo fibers, which are known for their high tensile strength and stiffness, provided structural reinforcement, while coconut coir added toughness and flexibility to the composite [32]. While the hybridization strategy provides advantages derived from both fiber types and is in line with sustainability goals, biodegradable and locally available materials can be incorporated into the process. This study showed that treated BAMCO ropes, with higher load-carrying capacity, can be a promising candidate for environmentally friendly geotextile applications.

4.6 Morphological Structure of the Untreated a Treated Fiber

Morphological structure gives an idea of the physical and microstructural characteristics of fibers. These traits determine the mechanical properties and durability of the fibers used in natural geotextile applications. It also accounts for the increase in tensile strength after the treatment of fibers with an alkaline solution.

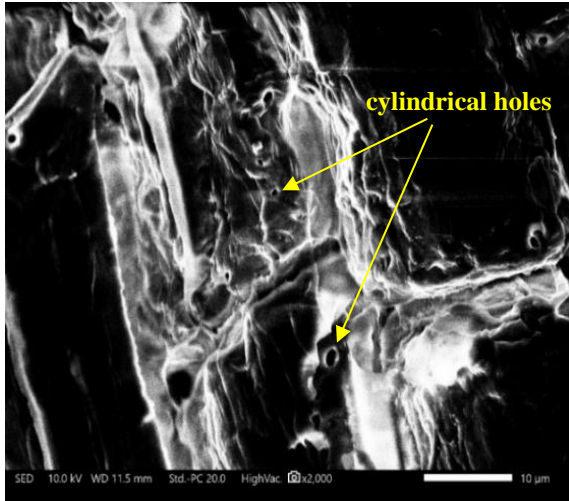


Fig. 14a Morphological structures of the untreated bamboo fiber with x2000 magnification

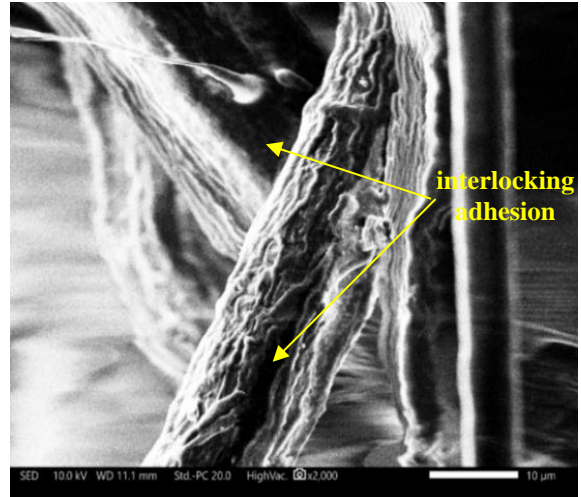


Fig. 14b Morphological structures of the treated bamboo fibers with x2000 magnification

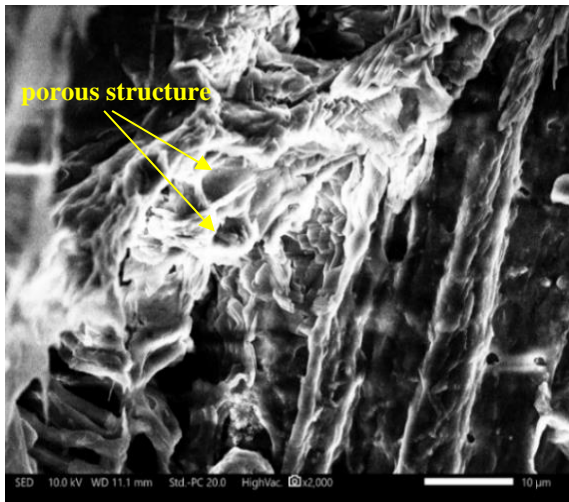


Fig. 15a Morphological structures of the untreated coconut fiber with x2000 magnification

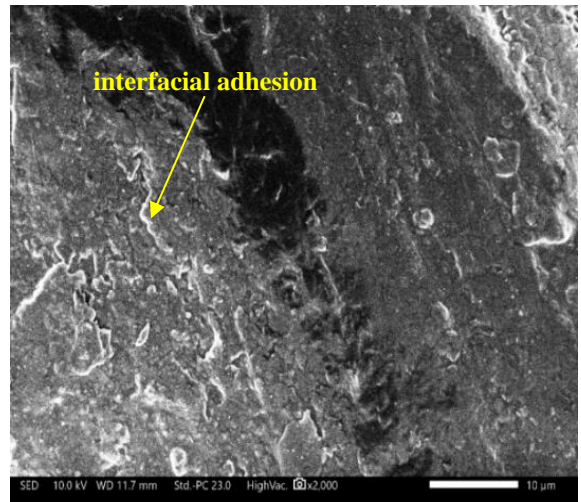


Fig. 15b Morphological structures of the treated coconut fiber with x2000 magnification

4.6.1. Morphological structure of the untreated and treated bamboo fiber

Fig. 14a and Fig. 14b represent the morphological structures of the untreated and treated bamboo fibers, respectively. Fig. 14a illustrates several holes and pores in the untreated fiber. But those are no longer visible in Fig. 14b, meaning the fiber became more structured after treatment. The results of the SEM analysis revealed that the alkali-treated bamboo fiber, as shown in Fig. 14b, exhibited a cleaner and more fibrillated surface compared to the untreated samples, as shown in Fig. 14a. This suggests that alkali-treatment had potentially enhanced the fibers' interfacial bonding. Additionally, it removed impurities such as lignin and exposed cellulose, thereby improving mechanical interlocking.

This explains the approximately 1.16-fold increase in the tensile strength of the treated fiber compared to the untreated sample.

4.6.2. Morphological structure of the untreated and treated coconut fiber

Fig. 15a and Fig. 15b show the morphological structures of the untreated and treated coconut fibers, respectively. Coconut fiber showed the same results as the bamboo fiber. Holes and cracks are visible in the untreated fiber in Fig. 15a. It also revealed that the alkali-treated coconut fiber had a cleaner, more fibrillated surface in Fig. 15b than the untreated sample. As shown in the image, the reduced pores influence the bond between fibers and matrix, which explains the improved mechanical property of coconut fiber by 10.43% after treatment.

Table 7. One-Way Anova results of untreated and treated bamboo and coconut fibers

Source of Variation	Sum of Squares (SS)	df	Mean Square (MS)	F	Fcrit (p < 0.05)	Decision
Between Groups	969.8532	3	323.2844	3414.38	4.066	Reject H ₀ (Significant difference)
Within Groups	0.7575	8	0.09468	—	—	—
Total	970.6107	11	—	—	—	—

Table 8. Post-Hoc test results of untreated and treated bamboo and coconut fibers

Comparison	Mean Difference (MPa)	Significance (p < 0.05)	Data Interpretation
Untreated Coconut vs Untreated Bamboo	10.60	Significant	Untreated bamboo fibers exhibit a much higher tensile strength than untreated coconut fibers.
Untreated Coconut vs Treated Coconut	0.20	Not Significant	Chemical treatment does not significantly change the tensile strength of coconut fibers.
Untreated Coconut vs Treated Bamboo	21.85	Significant	Treated bamboo fibers have dramatically higher tensile strength compared to untreated coconut fibers.
Untreated Bamboo vs Treated Coconut	10.40	Significant	Untreated bamboo fibers still show far greater tensile strength than treated coconut fibers.
Untreated Bamboo vs Treated Bamboo	11.25	Significant	Treatment further increases the already high tensile strength of bamboo fibers.
Treated Coconut vs Treated Bamboo	21.65	Significant	Treated bamboo fibers possess significantly higher tensile strength than treated coconut fibers.

4.7 STATISTICAL ANALYSIS

Table 7 presents the One-Way Anova results of untreated and treated bamboo and coconut fibers. The one-way ANOVA revealed a highly significant difference in tensile strength among the four fiber groups—untreated coconut, untreated bamboo, treated coconut, and treated bamboo. This suggests that the type and treatment of fibers have a substantial effect on their mechanical performance. The computed F-value of 3414.38 exceeded the critical F-value of 4.066 at the 0.05 significance level, hence the null hypothesis that all group means are equal is rejected. This large discrepancy reflects that the variability between groups is greater than the variability within groups, showing that differences in material type and the application of mercerization influence tensile strength. These findings confirm that fiber classification and treatment processes are critical factors in determining tensile behavior, warranting further post-hoc analysis to identify which specific groups differ from each other.

Table 8 revealed substantial differences among most fiber type pairs, confirming the strong effect of both fiber species and chemical treatment on tensile strength. The computed HSD critical value of 0.8046 MPa served as the threshold for determining significance; any pairwise mean difference exceeding this value indicates a statistically meaningful separation between treatments. Results showed that

untreated coconut and treated coconut fibers did not differ significantly, as their mean difference (0.20 MPa) fell well below the HSD value, suggesting that NaOH treatment does not noticeably enhance the tensile capacity of coconut fibers. In contrast, all comparisons involving bamboo—whether untreated or treated—exhibited very large mean differences (ranging from 10.40 to 21.85 MPa), far surpassing the HSD threshold. This strong statistical separation confirms that bamboo fibers inherently possess much higher tensile strength than coconut fibers, and that treatment further amplifies this advantage.

5. CONCLUSIONS

This study highlights the effectiveness of alkaline treatment using sodium hydroxide (NaOH) in enhancing the tensile strength of both bamboo and coconut fibers, including their twined and roped forms. Untreated bamboo fibers had significantly higher tensile strength than untreated coconut coir fibers by 63.89%, due to the fact that they contain more cellulose. Although coir fibers have high flexibility and good endurance, by their very nature they have low tensile strength. This performance discrepancy of bamboo reveals its mechanical advantages, making it an eligible material for natural fiber composites. This performance discrepancy of bamboo reveals its mechanical advantages, making it an eligible material for natural fiber composites. The

increase in tensile strength of bamboo during the treatment is by about 7.9x (from 3.02315 MPa to 26.9175 MPa). Coconut fiber also shows a similar trend, rising from 1.84457 MPa to 2.61863 MPa, thus making it 41.96% stronger following the use of treatment. The tensile strength of these fibers after transforming them into twines was greatly enhanced from 19.35% up to 35.02% especially after treatment with NaOH. Additionally, a higher load-carrying capacity is found in a rope of blended (bamboo-coconut) BAMCO fiber than in single fiber twine. The hybrid configuration utilizes the strengths of the specific fiber types: bamboo's rigidity and strength, and coconut coir's toughness and resilience. Overall, BAMCO rope shows potential for short-to-medium-term geotextile applications; further durability and field performance testing are required. This study recommends investigating the mechanical properties and effectiveness of a blended bamboo-coconut (BAMCO) rope for relevant geotechnical applications. Specific follow-up tests can be conducted, such as accelerated aging, tensile retention after wet-dry cycles, biodegradation rate, hydraulic permeability of woven blankets, and small-scale field trials for slope protection.

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