

Oil and Silane Surface Treatment of Bamboo Fibers for Improved Hydrophobicity and Strength Retention in Angled Composites

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Effects of different surface treatments were studied relative to the moisture absorption, tensile strength, and interfacial strength were compared for bamboo fibers with epoxy resin. The results showed that the bamboo fibers treated with palm oil had relatively good hydrophobicity and bonding strength with epoxy, and less influence on the tensile strength. Palm oil treatment at 150 °C decreased the strength of bamboo fibers, but it enhances the strength of angled bamboo fibers compared to that without oil treatment. Subsequently, tensile strength retention of angle-shaped bamboo fibers was investigated. The results showed that bamboo fibers treated with palm oil before preforming was able to improve the tensile strength after forming (from 222 to 252 MPa). The study also highlighted the process sequence of the surface treatments for improved strength retention after forming.

DOI: 10.15376/biores.21.2.4620-4642

Keywords: Vacuum forming; Oil treatment; Interfacial strength; Bamboo fiber; Tensile strength retention after forming; Bamboo fiber composite

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INTRODUCTION

The applications of natural fiber reinforced composites are increasing gradually due to their advantages such as cost-effectiveness, eco-friendliness, renewability, and full or partial biodegradability. These composites exhibit excellent mechanical properties and can serve as alternatives to synthetic fibers such as glass fibers and carbon fibers, *etc.* (Keya *et al.* 2019). Common plant fibers used in the manufacturing of composite materials include jute, hemp, flax, bamboo, and sisal. Among these, bamboo is widely utilized as a natural fiber due to its abundant yield, short growth cycle, and excellent mechanical properties (Lau *et al.* 2018). However, bamboo's widespread applications are limited due to its high porosity, its tendency to absorb moisture, the challenge of extracting fine and continuous fibers, and thermal deterioration during the production process (Zakikhani *et al.* 2014). Raising the moisture level in bamboo fibers results in a reduction in their mechanical strength (Asyraf *et al.* 2022; Ahmad *et al.* 2025).

Bamboo material consists of many vascular bundles and parenchyma cells. The fiber bundles in vascular bundles are arranged in a polygonal, honeycomb-like structure, with the fibers growing longitudinally along the bamboo. This longitudinal arrangement gives bamboo excellent tensile and bending strength, enhancing its mechanical properties (Tsuchikawa and Kobori 2015; Chen *et al.* 2018; Osorio *et al.* 2018; Rusch *et al.* 2023).

The preparation method used affects the quality and strength of bamboo fibers. Bamboo fibers can be obtained using physical, mechanical, or chemical methods. Chemical methods are typically more effective than physical or mechanical methods. Common chemical treatments include alkali treatment, acid neutralization, and enzymatic fermentation. Of these methods, alkali treatment efficiently eliminates impurities from the surface of bamboo fibers, creating a rougher texture that enhances adhesion with polymer matrices and strengthens composite materials. (Huang and Young 2019; Salih *et al.* 2020; Ebissa *et al.* 2022). Alkali treatment removes non-crystalline materials including hemicellulose, lignin, and wax from bamboo fibers, thereby increasing their crystallinity. Optimizing the alkali concentration and treatment duration can enhance bamboo fibers density, improve mechanical properties, and reduce moisture absorption of bamboo fibers (Akinyemi *et al.* 2020; Salih *et al.* 2020; Saha and Kumari 2023).

Thermal oil treatment of bamboo effectively reduces their moisture absorption. High temperatures during this process lead to the thermal breakdown of hemicellulose in bamboo, resulting in decreased moisture absorption and potentially affecting their mechanical properties (Vanleeuw *et al.* 2015; Yuan *et al.* 2020; Shettigar *et al.* 2025). Cellulose does not significantly degrade at 150 °C, but it can weaken if heated long enough (*e.g.* >1 hour) (Zhang *et al.* 2022). Appropriate oil treatment time and temperature can enhance the flexural strength of bamboo. At the suitable oil-treatment temperature, thermal activation promotes cellulose recrystallization and concentrates lignin within the fiber matrix. The combined increase in crystalline order and lignin-mediated cross-linking improves microfibril cohesion, leading to enhanced flexural performance of bamboo. (Tang *et al.* 2019; Hao *et al.* 2021; Piao *et al.* 2022). Oil treatment at 100 °C significantly improves the flexural strength of bamboo compared to untreated bamboo (Tang *et al.* 2019). However, within this temperature range, it is observed that flexural strength decreases with treatment temperature rising from 100 to 200 °C. Therefore, oil treatment below 140 °C is more effective for the flexural strength retention of bamboo.

Applying silane to bamboo fibers improves the interfacial bonding between the fibers and polymer matrices (Wang *et al.* 2020), thereby enhancing the overall mechanical properties of the composite material. Most studies on the oil treatment have concentrated on the moisture resistance and flexural strength of large-size bamboo. There have been limited studies on the tensile strength of bamboo fiber with oil treatment (Mebratie *et al.* 2023).

In manufacturing of composites with complex shapes, various curved forms may be involved in the part. Therefore, it is crucial to assess the feasibility for fabricating a part with a simple curved shape. There have been few published studies that focused on the strength retention of the bamboo fiber after deformation. In previous studies, carbon fiber or glass fiber has been used to fabricate curve-shaped composites by vacuum forming, but there is a need for related studies involving bamboo fiber. The moisture content of bamboo fibers before preforming affects the forming effectiveness (Chiu and Young 2020; Shih and Young 2022; Wang and Young 2022). Preforming of bamboo fibers at a saturated moisture level can reduce the occurrence of rebounding. After preforming, angle-shaped bamboo fibers show a significant decrease in tensile strength (Hsu and Young 2024).

This study investigated the strength retention at the angle point of the bamboo fiber after angle-shaped preforming, exploring the impact of surface treatments and different preforming conditions on the tensile strength of angle-shaped bamboo fibers. A fixed angle of 135° was used to preform the bamboo fiber. Different oil treatments on bamboo fibers were conducted to determine the most suitable process that has good combination of

moisture resistance, strength, and interfacial strength after treatment. Subsequently, the research considered how surface treatments and preforming conditions affect the tensile strength of angle-shaped bamboo fibers.

Based on existing studies describing the effects of thermal oil treatment on lignocellulosic materials, it is hypothesized that oil treatment may enhance the flexibility and damage tolerance of bamboo fibers, particularly under bending or curved composite configurations. Prior research has shown that oils such as palm, avocado, and tung oil can partially plasticize or soften the cell wall, reduce surface microcracking, and form a hydrophobic coating that redistributes interfacial stresses. These mechanisms also improve compatibility with polymer matrices by lowering surface energy and providing a more compliant, uniform interphase. Therefore, it is proposed that oil treatment could mitigate fiber damage during bending while simultaneously improving interfacial performance—an effect consistent with the mechanisms described in the literature (Tang *et al.* 2019).

EXPERIMENTAL

Material

The bamboo strips utilized in the experiment were sourced from Makino bamboo (*Phyllostachys makinoi*), cultivated in Taiwan and harvested at the age of 5 years. The receipt bamboo strip was in size of $1800 \times 3.7 \times 1.2$ mm³. This study employed a mechanical processing method to extract bamboo fibers through cutting. The portion close to the bamboo skin was used. The final dimensions of the bamboo fibers were 1.0 (width) \times 0.7 (thickness) mm² in cross-section and 85 mm in length. A caliper was used to measure the thickness and width of the bamboo fiber, and 10 samples were measured to have the average value.

The bamboo fibers were subjected to alkaline treatment. Based on the literature (Chiu and Young 2020), the alkaline treatment procedure consists of soaking the bamboo fibers in a sodium hydroxide solution (5 wt.%) for 2 h at room temperature, then drying them in an oven at 80 °C for 6 h. For the vacuum forming process, the vacuum bag used was WRIGHTLON® 7400 and the sealant tape was AT-200Y, both supplied by Airtech. The epoxy resin used was model ML3564, and the hardener was model HY3954, both provided by Golden Gate Chemical, Taiwan. ML 3564 Resin and HY 3954 hardener are commonly used in the production of advanced composite materials, particularly in applications involving epoxy resin systems. ML 3564 is an epoxy resin with reactive epoxide groups and HY 3954 is a hardener based on amine chemistry. Silane OFS-6341 (n-Octyltriethoxysilane, also known as Triethoxy(octyl)silane) purchased from Dow were employed to formulate silane solutions.

Oil and Silane Treatment

Different oils including avocado oil, palm oil, soybean oil, and tung oil were used to treat the bamboo fibers. When treating bamboo fibers, natural oils are often preferred due to their ability to enhance the properties of the fiber without introducing harsh chemicals. The selection of these oils was because they have superior water resistance and durable finish when cured. They are also non-toxic and environmentally friendly, making them ideal for treating bamboo fibers in eco-conscious products. The oils were purchased from the food market. Before oil treatment, the bamboo fiber were dried in an oven at 80 °C for 6 h. The oil treatment procedure included heating the oil to 150 °C and immersing

the bamboo fibers in it for 1 h. Following the oil treatment, the fibers were dried in an oven at 80 °C for 6 h. To examine the effect of temperature during oil treatment, bamboo fibers were processed using palm oil at varying temperatures of 100, 150, and 180 °C, with each treatment involving immersion in the oil for 1 h, subsequently dried in an oven at 80 °C for 6 h

A silane aqueous solution was prepared by mixing 5 wt.% silane (Silane-6341), 20 wt.% alcohol (95% in concentration), and 75 wt% distilled water. Adding alcohol helps the silane dissolve better in water. The bamboo fibers were soaked in the silane aqueous solution at room temperature for 30 min, using a magnetic stirrer to increase the contact area between the bamboo fibers and the silane solution. After soaking, the bamboo fibers were set in a hot air circulation oven and dried at 80 °C for 6 h.

Density and Moisture Absorption

The bamboo fibers, after undergoing the oil treatments, were then cut into lengths of 45 mm for the density and moisture tests. The weight of bamboo fibers was measured using an electronic scale. By observing the water displacement in a glass cylinder when the fibers are submerged, and applying Archimedes' principle, the volume of the bamboo fibers were determined. With both weight and volume known, the density of the bamboo fibers can then be calculated.

Bamboo fibers were put in an oven at 80 °C for 2 h to reach a dry state. The original weight of the fiber was measured using an electronic scale. After that, the fibers were immersed in water for 90 min to reach saturation, with measurements of their weight taken every 10 min. The moisture absorption was calculated for the bamboo fiber as follows:

$$M_w = \frac{W_{\text{wet}} - W_{\text{dry}}}{W_{\text{dry}}} \times 100\% \quad (1)$$

where M_w represents the moisture absorption of the bamboo fiber, w_{wet} represents the weight of the wet bamboo fiber, and w_{dry} represents the weight of the dry bamboo fiber. The tests for moisture absorption were replicated five times to derive the average value.

Interfacial Shear Strength

The oil treatment was applied to the bamboo fiber to improve its moisture resistance and enhance its ability to retain tensile strength. However, applying oil treatment might affect the bond strength between the fiber and the matrix due to the variation of the hydrophobicity, surface roughness, and compatibility with the epoxy. Therefore, interfacial shear strength tests were conducted for bamboo fibers under different surface treatments. A form was designed to prepare the samples for the interfacial shear strength test. The form was created using Solidworks software and then 3D printed to produce the physical fixture, as shown in Fig. 1.

Since epoxy resin is a commonly used matrix in fabrication of bamboo fiber composites, it was used as the matrix for testing the interfacial shear strength between the bamboo fiber and matrix. During sample preparation, the resin and curing agent were combined in a weight ratio of 100:35 and then poured into the mold. The fibers were embedded into the resin to a depth of 2 mm and securely held in place by the fixture as depicted in Fig. 1. The resin is then cured at 80 °C for 2 h to achieve complete solidification. A 2 mm embed length avoids shear-lag artefacts because it is larger than the stress-transfer (shear-lag) length for typical bamboo fibers/bundles. Bamboo fibers have high roughness and lumen structure, further reducing effective transfer length. Test with a longer embed

length will result in fiber breakage instead of pullout.

The interfacial shear strength test was carried out using a micro tensile test machine, as shown in Fig. 2, with a pulling speed set at approximately 2 mm/min following the procedure in literature (Huang and Young 2019). This controlled speed ensured consistent and accurate measurements during the test. To calculate the interfacial shear strength, a formula was employed in Eq. 2. The value obtained from this calculation represented the strength of the interface between the bamboo fiber and the epoxy matrix, giving insights into the effectiveness of the interface for composite material applications.

$$\tau = \frac{F}{PL} \quad (2)$$

In Eq. 2, τ represents the interfacial shear strength, F represents the maximum load applied before bamboo fiber separate from the epoxy, P represents the circumference of the bamboo fiber, and L represents the embedding depth of the fiber into the epoxy. The tests for interfacial shear strength were replicated 5 times to derive the average value.

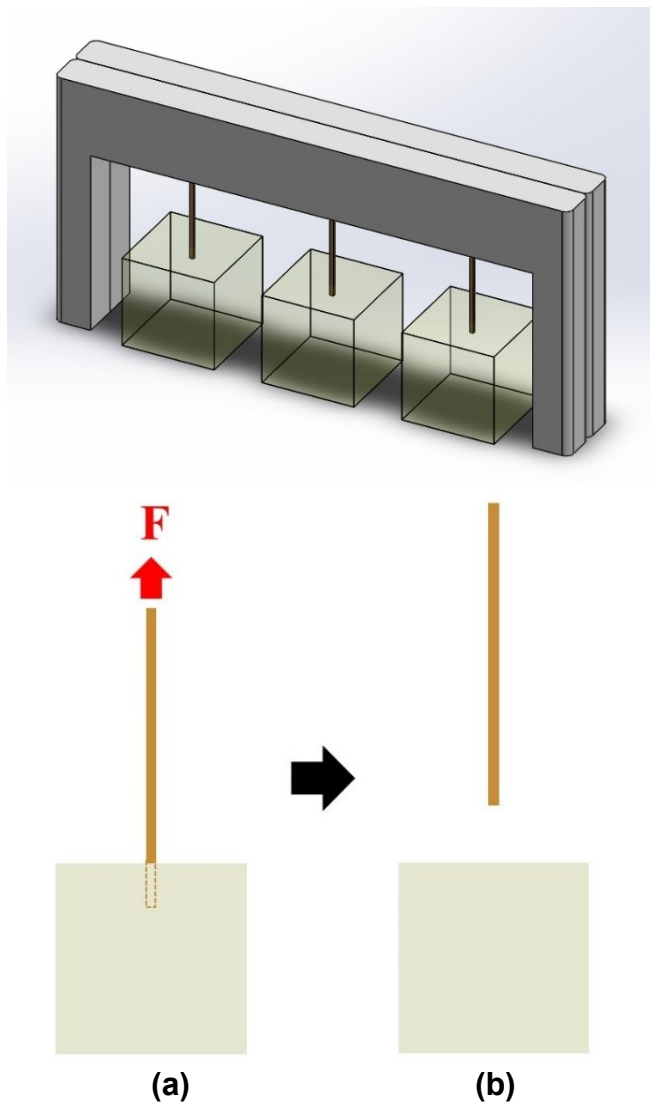


Fig. 1. (a) Fiber/epoxy bonding setup and (b) interfacial shear strength test



Fig. 2. Photograph of the micro-test machine

Vacuum Preforming

The mechanical strength, water absorption, and bonding degree were determined for epoxy composites of bamboo fibers that had been subjected to different surface treatments. Among the various choices of plant oils, palm oil treated at 150 °C was selected as the fixed oil treatment process for subsequent vacuum preforming studies. The multi-rounded corner preform mold was used for vacuum preforming of bamboo fibers (Hsu and Young 2024). The middle mold bends were all at an angle of 135°, but with different radii of rounded corners, specifically with radii of 0, 2, 4, 6, 8, and 10 mm as shown in Fig. 3. This study primarily examined how various surface treatments and preforming conditions impact the retention of tensile strength. Therefore, only the area with a radius of 2 mm was used to preform bamboo fibers.

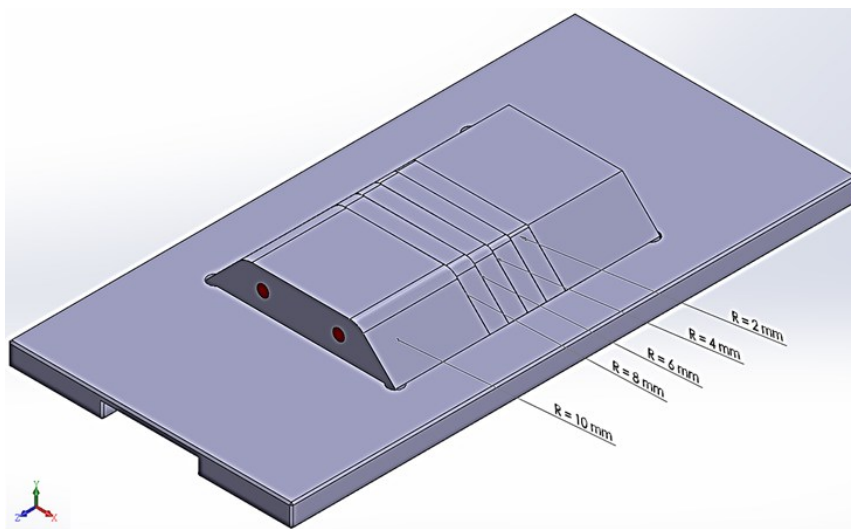


Fig. 3. The preform mold with an angle of 135° (Hsu and Young 2024)

All surface-treated bamboo fibers were dried before the forming process. The vacuum preforming process included cutting the surface treated bamboo fibers into 85 mm lengths, placing them on a mold, and wrapping them with a vacuum bag and sealant tape, as shown in Fig. 4.

If water immersion of the bamboo fibers was applied before preforming, the immersion time is 1 hour. The immersion time was selected to reach moisture saturation based on the bamboo fiber moisture absorption tests. Subsequently, vacuum pressure was applied during preforming, while heating to 120 °C for 1 h. After heating, the vacuum was maintained for an additional 4 h for cool down to room temperature. The schematic diagram of the preforming process and the bamboo fiber after deformation are shown in Fig. 5(a). An angle-shaped fiber was cut from the preformed fiber, as shown in Fig. 5(b). The tensile test specimen was cut from the angle-shaped bamboo fiber from the bend outward, extending 25 mm on each side, as shown in Fig. 5(c).

To examine how oil treatment affects the tensile strength of angle-shaped bamboo fibers, four different surface treatments were used for the bamboo fibers before the vacuum preforming. The first one used the alkaline treated bamboo fibers for preforming, and this will serve as the control group. The second group submerged the alkaline treated fibers in palm oil at 150 °C for 1 h. Third group applied the silane treatment for the fibers after alkaline and oil treatment. The fourth group soaked the fibers of third group into the distilled water for 1 h before preforming.

To further explore how preforming conditions influence the tensile strength of angle-shaped bamboo fibers, three additional preforming conditions were examined: using different preforming temperature, incorporating a Caul Plate (lead plate) during the preforming process, and preheating the bamboo fibers before preforming.

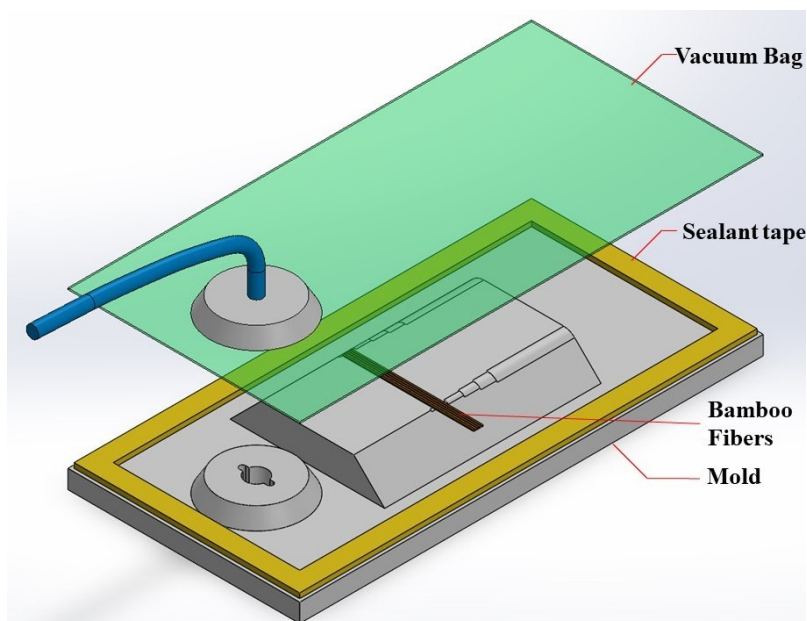


Fig. 4. The setup for vacuum preforming of angle-shaped bamboo fibers

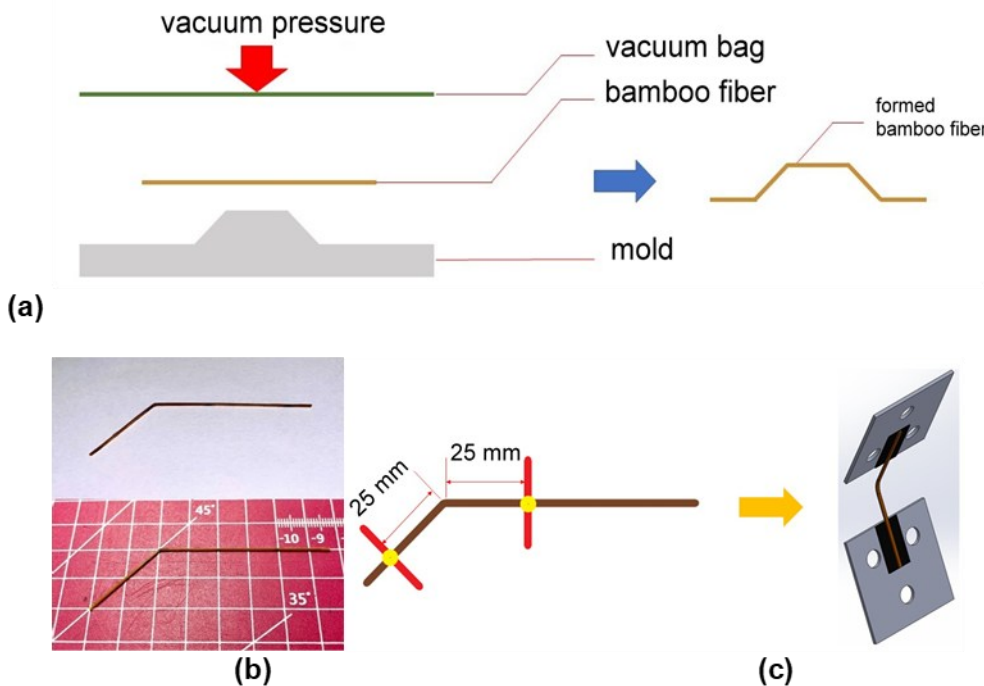


Fig. 5. (a) The setup for vacuum preforming of angle-shaped bamboo fibers (b) the cut angle-shaped fiber (c) angle-shaped bamboo fiber test sample

Tensile Strength of Bamboo Fibers

The bamboo fibers, which have been treated as described above, are now being prepared by cutting them into lengths of 4.5 centimeters. These surface-treated bamboo fibers are then subjected to tensile testing using a micro-tensile testing machine. In the micro-tensile tests, the bamboo fibers were prepared by cutting them into pieces measuring 45 mm in length, 0.7 mm in thickness, and 1 mm in width for unbent bamboo fibers. To conduct the tests, a custom-made micro tensile test machine, depicted in Fig. 5, was utilized. This device enabled the simultaneous measurement of load and displacement using a 700 N load cell and an optical ruler with a resolution of 1 μm . Five samples were prepared for each tensile test.

The tensile tests were conducted at room temperature (25 $^{\circ}\text{C}$), and the bamboo fiber samples were in a dry condition. To prepare the test specimen, both ends of a single fiber were meticulously bonded between sandpapers and aluminum fixtures. Sandpaper was employed to protect the bamboo fiber from damage during clamping and to improve adhesion to the fixture. Tensile tests were performed at a pulling speed of 3 mm/min to guarantee precise and consistent results. This configuration allowed for precise assessment of the tensile strength and performance of the bamboo fibers under the given conditions. Figure 6 displays the samples of both straight and angled, deformed bamboo fibers. The tensile test for angle-shaped bamboo fibers was carried out following established literature guidelines (Hsu and Young 2024). The angle-shaped bamboo fibers, each cut to a total length of 50 mm, were fastened onto specimens using sandpaper, as shown in Fig. 6(b). Based on the literature, the tensile test of this bent shaped sample was similar to that of bamboo fiber with restored bent section. The tests for tensile strength and modulus were replicated 5 times to derive the average value.

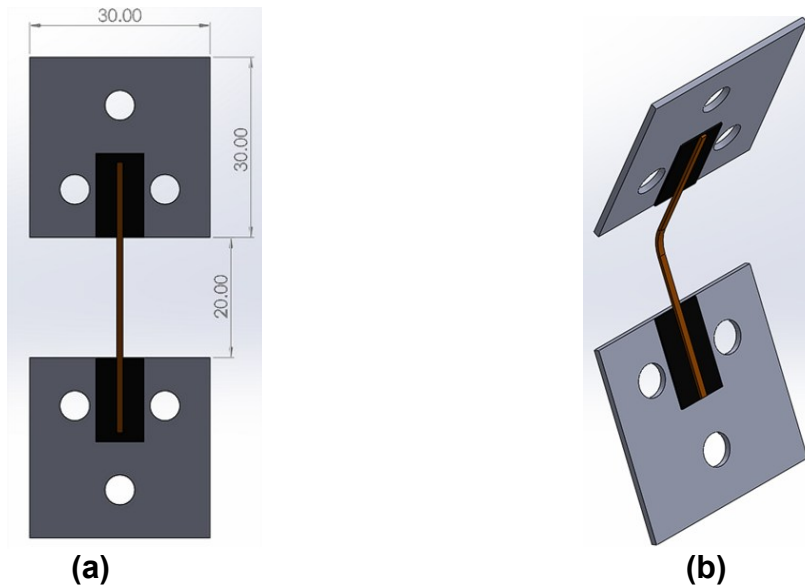


Fig. 6. Tensile test specimen for (a) straight and (b) deformed angle-shaped bamboo fiber (Hsu and Young 2024)

RESULTS AND DISCUSSION

Density and Moisture Absorption of Bamboo Fibers

To facilitate the discussions, surface treatment processes are denoted by codes as shown in Table 1. The codes U and A are related to whether an alkaline treatment was applied on the bamboo fibers. Among the oil treatments, avocado oil, palm oil, soybean oil, and tung oil are represented by the letters V, P, S, and T. The oil treatment temperature is also included in the code for 100, 150, and 180 °C. Besides, S represents the silane treatment. For all the cases with silane treatment, the oil treatment temperature was 150 °C, which was omitted to simplify the code.

The density was 0.97 g/cm³ for the untreated bamboo fiber. After alkali treatment, the density increased to 1.10 g/cm³, as shown in Fig. 7. This increase is likely due to the alkali treatment's effectiveness in dissolving and removing fatty acids and triglyceride fats from the material, that such removed is likely to have a positive effect on subsequent adhesion within the material. (Kalia *et al.* 2009; Wong *et al.* 2010; Kumar and Mohanraj 2017). After heating bamboo fibers with various types of oil at 150 °C for 1 h, their density increased to 1.21 to 1.24 compared to 1.10 of alkali-treated bamboo fibers. This is likely because, at 150 °C, it does not excessively degrade the cellulose and hemicellulose in the bamboo structure, thus having minimal impact on the weight of the bamboo fibers (Hao *et al.* 2021). On the other hand, oil may penetrate into the voids of bamboo fiber cells and adhere to the bamboo cell structure. It also creates a layer of oil film on the bamboo fiber surfaces, demonstrated by the dark color after the oil treatment. As a result, the density of the oil-treated bamboo fibers rises due to the absorption of the oils.

Figure 8(a) compares the moisture absorption of bamboo fibers treated with different oils at a temperature of 150 °C. Following different oil treatments, the moisture absorption values for the bamboo fibers were lower compared to those of alkali-treated bamboo fibers. This occurs because the cell walls of bamboo fibers are covered with an oil film that obstructs most of the pores within the fibers, thus preventing water penetration.

Additionally, oils on the surface of bamboo fibers form a hydrophobic layer, imparting excellent waterproof properties. Specifically, bamboo fibers treated with palm oil at 150 °C for 1 h exhibit the lowest moisture absorption rate at 32.55%. Palm oil, being more saturated and chemically stable, forms a uniform, flexible, hydrophobic layer that does not crack easily. This can make water resistance better, even without chemical bonding. Palm oil often has lower viscosity at elevated temperatures and smaller molecular packing (due to saturation). This helps it penetrate deeper into lumen and cell wall pores. Thus, it can be more effective in blocking moisture pathways and creating a more continuous hydrophobic barrier. Figure 8(b) illustrates the impact of oil treatment temperature on the water uptake of bamboo fibers. As the treatment temperature of the bamboo fiber increases, the moisture absorption decreases. This observation is consistent with the literature (Yuan *et al.* 2020; Piao *et al.* 2022), where higher processing temperatures lead to thermal degradation and the loss of cellulose and hemicellulose within bamboo fibers. This degradation reduces their capacity to absorb moisture.

Table 1. The Codes of Surface Treatment Processes

Code	Treatments
U	Untreated
A	5 wt.% Alkali
AV150	5 wt.% Alkali + 150 °C Avocado oil
AP150	5 wt.% Alkali + 150 °C Palm oil
AS150	5 wt.% Alkali + 150 °C Soybean oil
AT150	5 wt.% Alkali + 150 °C Tung oil
AP100	5 wt.% Alkali + 100 °C Palm oil
AP180	5 wt.% Alkali + 180 °C Palm oil
AVS	5 wt.% Alkali + 150 °C Avocado oil + 5 wt.% Silane
ASS	5 wt.% Alkali + 150 °C Soybean oil + 5 wt.% Silane
APS	5 wt.% Alkali + 150 °C Palm oil + 5 wt.% Silane
ATS	5 wt.% Alkali + 150 °C Tung oil + 5 wt.% Silane

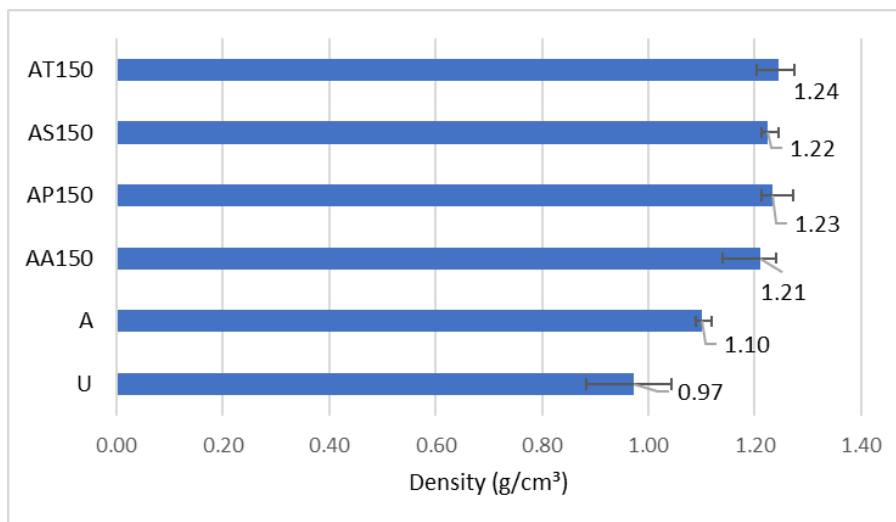
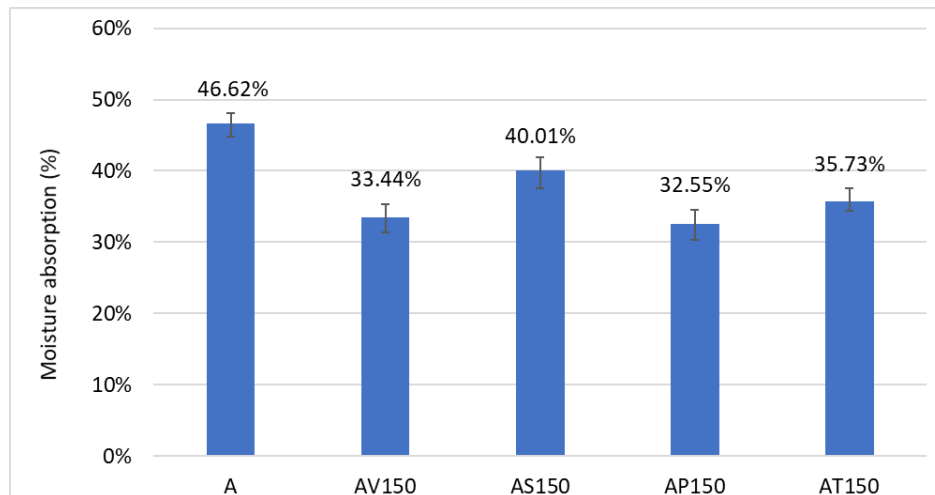
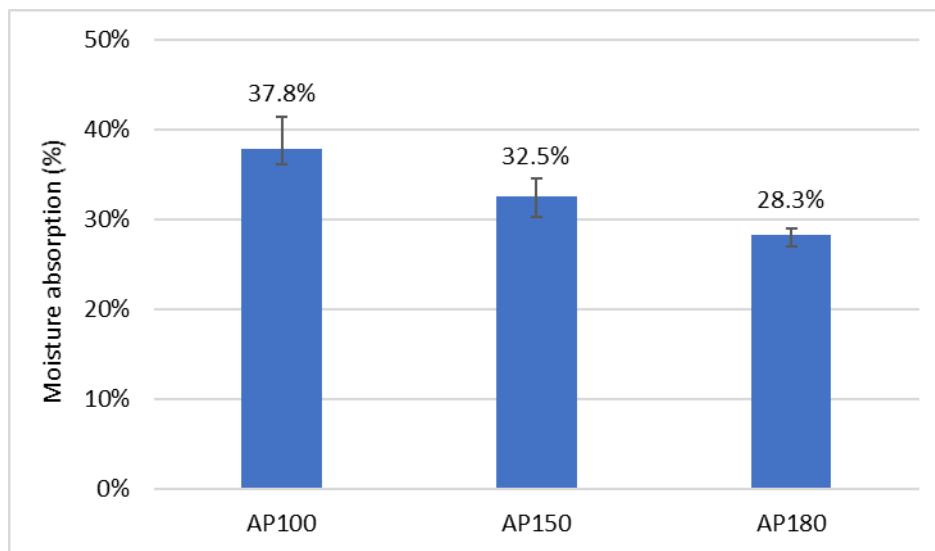


Fig. 7. Density of bamboo fibers before and after alkaline and oil treatments



(a)



(b)

Fig. 8. Moisture absorption of bamboo fibers for (a) different oil treatments and (b) different treating temperature

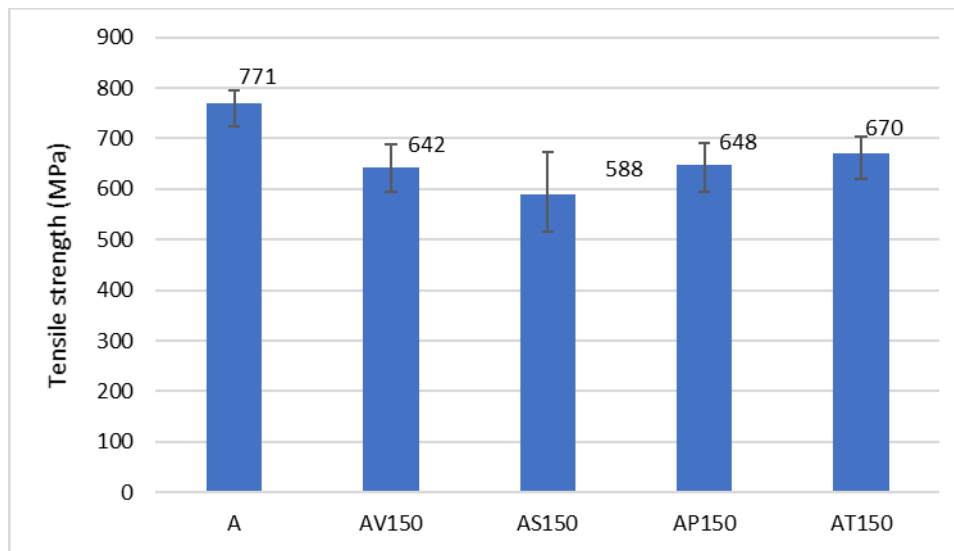
Tensile Strength of Bamboo Fibers

In this section, the various oil treatments were assessed for their effect on the mechanical properties of bamboo fibers. These fibers are expected to be integrated with epoxy in the future to produce bamboo fiber composite materials. Studies in the literature have explored how oil treatment affects the mechanical properties of bamboo or scrimber. The studies were typically assessed using bending tests to measure flexural strength, while the effect on tensile strength was not evaluated (Tang *et al.* 2019; Yuan *et al.* 2020; Hao *et al.* 2021; Piao *et al.* 2022). This study investigated the influence of different oil treatments on the tensile strength of a single bamboo fiber with a cross-sectional area of $0.7 \times 1.0 \text{ mm}^2$.

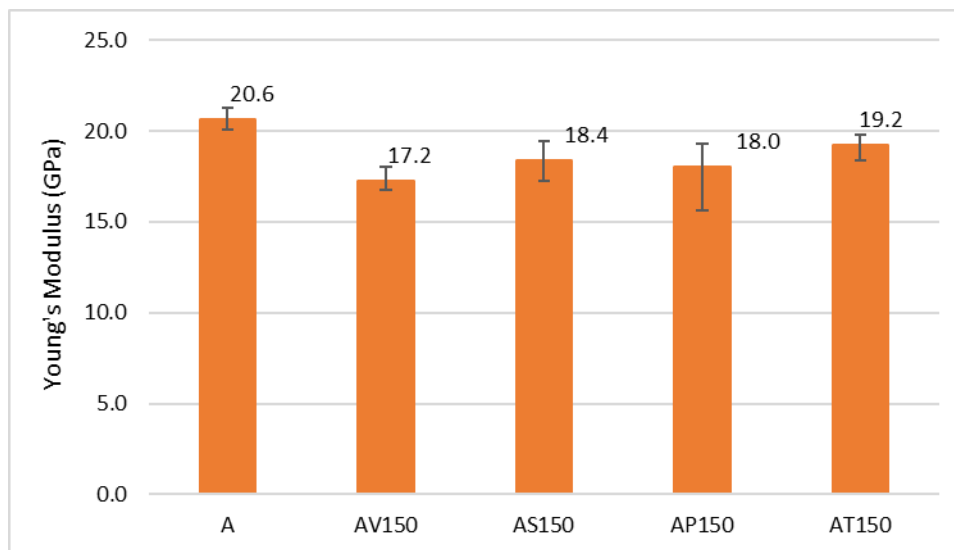
Figure 9 displays the tensile strength and modulus of bamboo fibers following alkaline and oil treatments. Alkali-treated bamboo fibers demonstrated a tensile strength of 771 MPa and a Young's modulus of 20.6 GPa. However, following various oil treatments, both the strength and modulus in tension for a single bamboo fiber were reduced. This decrease is attributed to the thermal degradation of cellulose and hemicellulose during the

oil treatment process, which leads to diminished mechanical properties (Cui *et al.* 2023). Among the different oil treatments, bamboo fibers treated with tung oil (AT150) exhibited the highest tensile strength at 670 MPa and a Young's modulus of 19.2 GPa, while those treated with palm oil achieved the second-highest tensile strength at 648 MPa. The typical stress-strain curves of the tensile tests for the bamboo fiber under different oil treatments are also shown in Fig. 9(c).

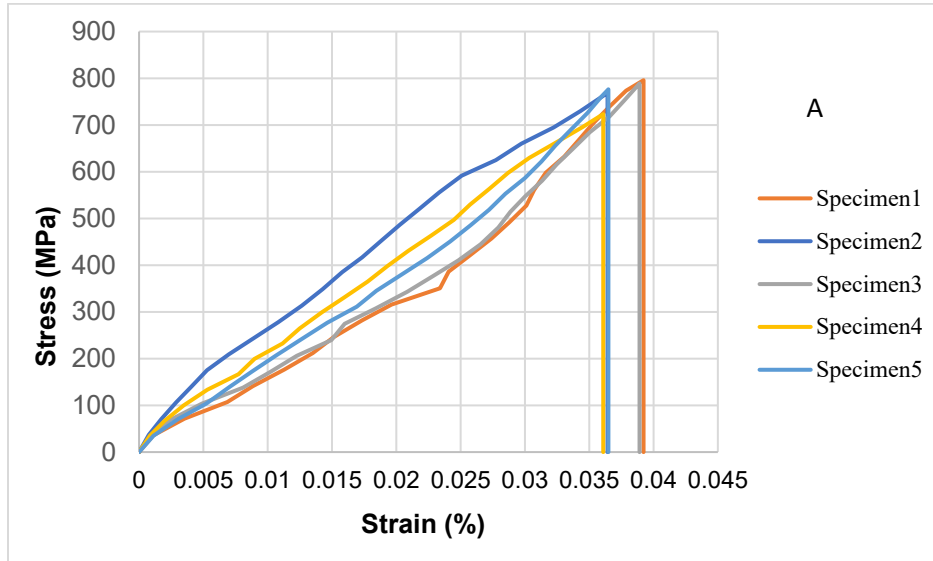
Considering both the moisture absorption and the mechanical property, palm oil was selected for investigation of the oil treatment at different temperatures. Figure 10 shows the strength and modulus in tensile test for bamboo fibers subjected to palm oil treatment at various temperatures. As the treatment temperature rose, both the strength and modulus of the bamboo fiber generally decreased. This trend is likely due to increased thermal degradation of cellulose and hemicellulose at higher temperatures, which diminishes the mechanical properties of the fibers.



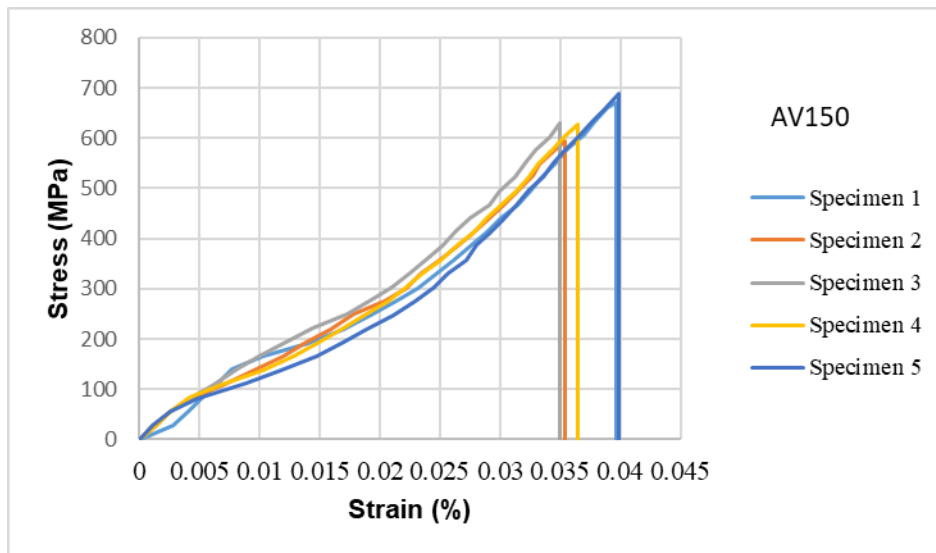
(a)



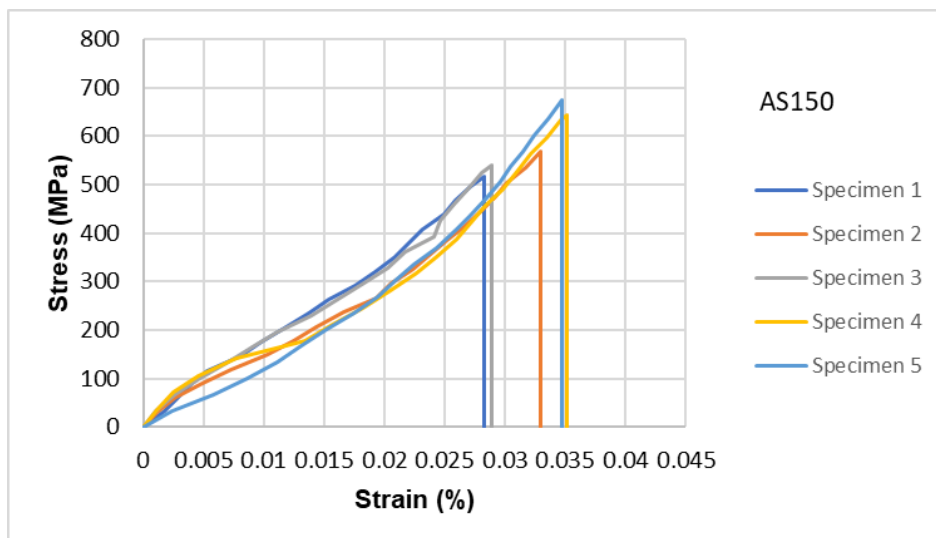
(b)



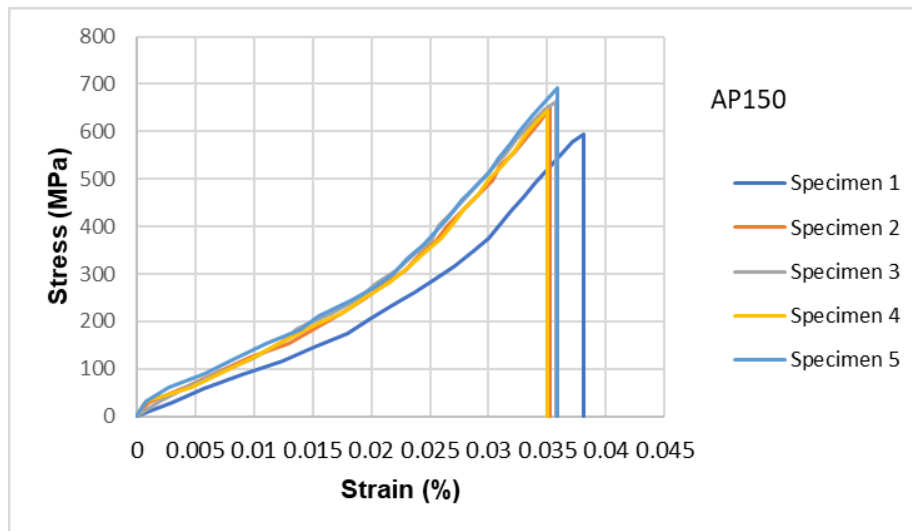
(c)



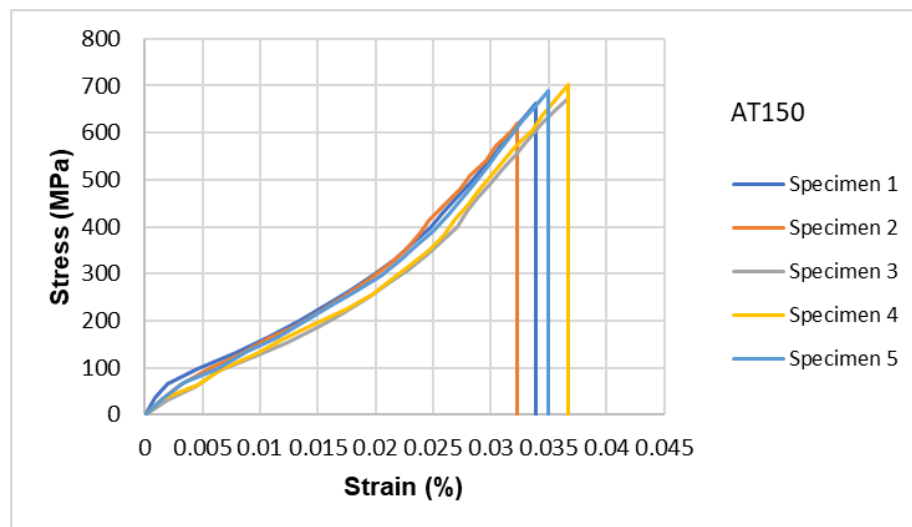
(d)



(e)



(f)

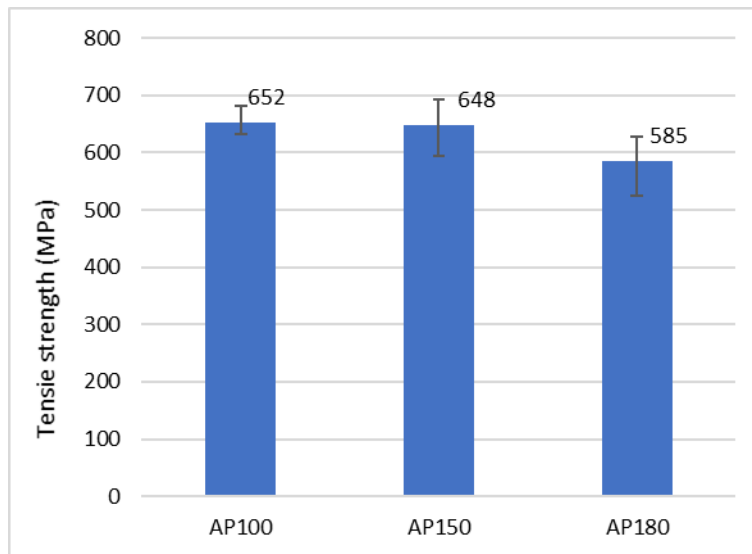


(g)

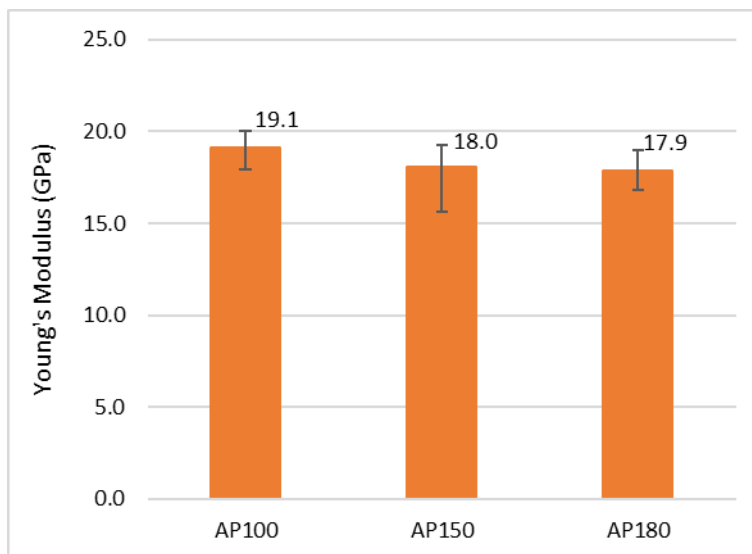
Fig. 9. (a) Strength and (b) modulus; stress-strain curves in tensile test of bamboo fibers under different (c) alkaline and oil treatments of (d) avocado (e) soybean (f) palm (g) tung oils

Fiber/Epoxy Interfacial Shear Strength

This section will evaluate how various oil treatments influence the interfacial shear strength between bamboo fibers and epoxy. Concerning moisture absorption and mechanical properties of bamboo fibers treated with oil at different temperatures, a treatment temperature of 150 °C was the most suitable condition. For the study of the interfacial strength, the oils treatment were applied at a temperature of 150 °C. Due to the potential reduction in bonding strength caused by oil presence on bamboo fiber surfaces, silane treatment was necessary to enhance their bonding. As shown in Fig. 11, bamboo fibers treated with both palm oil followed by silane (APS) exhibited the highest interfacial shear strength with epoxy among all cases, showing higher values compared to bamboo fibers treated only with alkali (A). This occurs because oil treatments can produce a hydrophobic surface on the fibers. However, applying oil treatment might affect the bond strength between the fiber and the matrix due to the variation of the hydrophobicity, surface roughness, and compatibility with the epoxy.



(a)



(b)

Fig. 10. Effect of treating temperature on (a) strength and (b) modulus in tensile test of bamboo fibers

This enhancement is attributed to silane acting as a coupling agent between bamboo fibers and epoxy, thereby strengthening their bonding.

Silane coupling agents are bifunctional molecules: their alkoxy groups hydrolyze to silanols which condense to form covalent Si–O–substrate bonds with surface hydroxyls on cellulose (or glass), and simultaneously the organofunctional tail (for example, glycidyl for epoxy systems, or amino groups for certain resins) reacts or co-polymerizes with the polymer matrix. Additionally, silanes can crosslink with one another to form a thin siloxane (Si–O–Si) network at the interface, improving load transfer, reducing interfacial defects and improving moisture resistance; the result is a chemical bridge that replaces weak physical contact with covalent/chemical coupling between fiber and resin (Zhi *et al.* 2017).

Based on these results, bamboo fibers treated with palm oil exhibited superior hydrophobicity and bonding strength with epoxy, along with the second-best mechanical properties. As the temperature of the oil treatment increased, the hydrophobicity of the

bamboo fibers improved, but their mechanical properties decreased. Consequently, for this study, the palm oil treatment at 150 °C was selected as the oil treatment process for the following fiber preforming study.

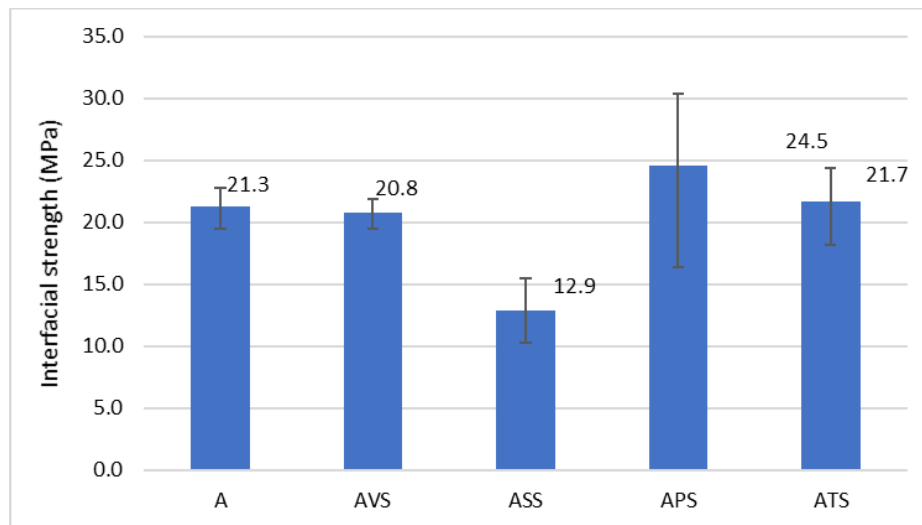


Fig. 11. Bamboo fiber/epoxy interfacial shear strength

Tensile Strength Retention of Angle-Shaped Bamboo Fibers

The hydrophobicity, mechanical properties, and resin bonding of bamboo fibers treated with different oils were evaluated. The results indicated that bamboo fibers treated with palm oil exhibited the highest hydrophobicity and resin bonding, while their mechanical properties ranked second. Therefore, palm oil was selected as the standard oil for treatment. Subsequently, by comparing the effects of different oil temperatures on the hydrophobicity and mechanical properties of bamboo fibers, 150 °C was selected to be the fixed oil treatment temperature. This section will discuss the effects of different surface treatments and preforming conditions on the strength retention of the bamboo fiber after curved preforming.

Codes will be used here to represent different treatment processes and various preforming conditions, as listed in Table 2. AWP represents the process of the alkaline treatment and water soaking before preforming. AOP represents the process of the alkaline treatment and palm oil soaking at 150 °C before preforming. AOWP represents the alkaline treatment, palm oil soaking at 150 °C, and water soaking before preforming. 140VH indicates the preforming process where the temperature is increased to 140 °C. 120CP represents the preforming process with the addition of a caul plate. 120HV represents the preforming process where the bamboo fibers are heated before vacuum forming. Due to the small cross-sectional area of angle-shaped bamboo fibers, a bending test could not be used to compare their strength. Instead, a tensile test was employed to examine the impact of oil treatment and different preforming conditions on the strength of angle-shaped bamboo fibers.

As shown in Fig. 12, alkali-treated bamboo fibers, preformed after soaking in water to achieve saturation (AWP), exhibited a tensile strength of 222 MPa. However, direct preforming after alkali and oil treatments (AOP) resulted in a decreased tensile strength of angle-shaped bamboo fibers to 141 MPa. It is speculated that the moisture content of the bamboo fibers before preforming significantly affects the strength at the angle-shaped point

after preforming. In the present experiments, the bamboo fibers were immersed in water for 1 hour to obtain saturation moisture before forming. Water can soften the bamboo fibers, thereby reducing damage to cellulose and hemicellulose during preforming (Shettigar *et al.* 2025). Consequently, not soaking the bamboo fibers in water before preforming will lead to a substantial reduction in tensile strength. If the oil-treated bamboo fibers are saturated by immersing them in water before preforming (AOWP), the tensile strength of angle-shaped bamboo fibers reached 252 MPa. According to references, oil treatment of bamboo fibers at appropriate temperatures enhances the crystallinity of cellulose and the proportion of lignin, thereby enhancing the bonding between cellulose and improving their bending strength (Tang *et al.* 2019; Hao *et al.* 2021; Piao *et al.* 2022). Oil treatment improves the flexural strength of bamboo fibers, which in turn boosts the tensile strength of angle-shaped bamboo fibers after preforming. From the results of this study, the pre-treating bamboo fiber with palm oil at 150 °C and saturating them with water before preforming can improve their tensile strength and reduce the strength degradation caused by preforming.

Table 2. Codes of Different Treatment Processes and Preforming Conditions

Code	Surface Treatments
AWP	5 wt.% Alkali + 1 hr Water + Preform
AOP	5 wt.% Alkali + 150 °C Palm oil + Preform
AOWP	5 wt.% Alkali + 150 °C Palm oil + Dry for 6 h + 1hr Water + Preform
Preforming Conditions	
140VH	Vacuum + Heating at 140 °C
120CP	Vacuum+ Caul Plate + Heating at 120 °C
120HV	Heating at 120 °C + Vacuum

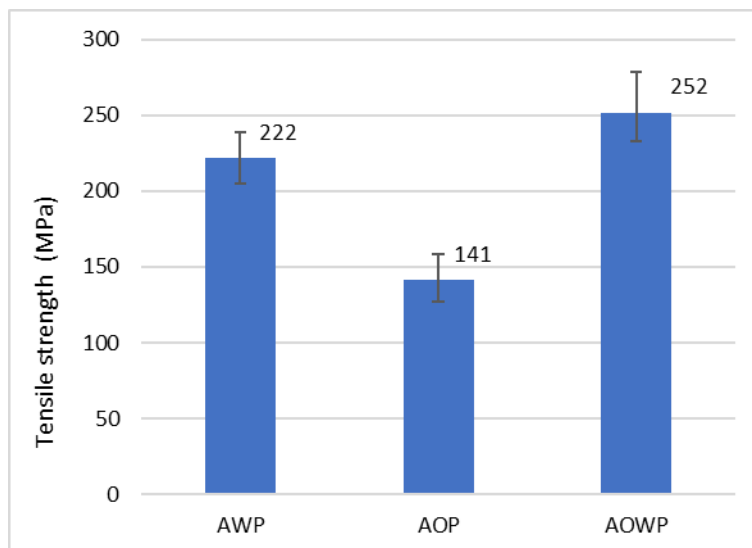


Fig. 12. Tensile strength of angle-shaped bamboo fiber by different surface treatment

Results from the single bamboo fiber tensile tests are shown in Fig. 13. Bamboo fibers are anisotropic (their properties vary along different axes). Breakage often occurs along the longitudinal direction, causing the fibers to split into smaller fibrils. This splitting is typical because bamboo fibers consist of bundles of smaller, aligned cellulose strands.

After breakage, the fiber ends may appear frayed or fuzzy, particularly if the breakage involved tension. Under a microscope, the broken ends reveal rough surfaces with cellulose fibrils protruding. Bamboo fibers exhibit fibrillation (separation into finer fibrils) upon breakage, reflecting their multi-layered structure. Figure 13(a) shows the characteristic behavior for the bamboo fiber after fracture, which has cellulose fibrils protruding and fibrillation. For angle-shaped bamboo fibers, the corner region sustains some damage during bending preforming, which becomes a weak point during tensile test. A relatively smooth fracture surface can be observed in Figs. 13(b) and (c) due to the early fracture at this weak region. Subsequent water treatment after oil treatment improved fiber–epoxy interfacial bonding and enhanced the formability of bamboo fibers during bending forming. This is likely due to removal of excess surface oil, partial swelling of the cell wall reactivating hydroxyl groups, and reduced microcracking, consistent with prior observations on oil-heat and post-wash treatments of bamboo and other lignocellulosic fibers (Tang *et al.* 2019). A schematic diagram is shown in Fig. 14 to show the mechanism.

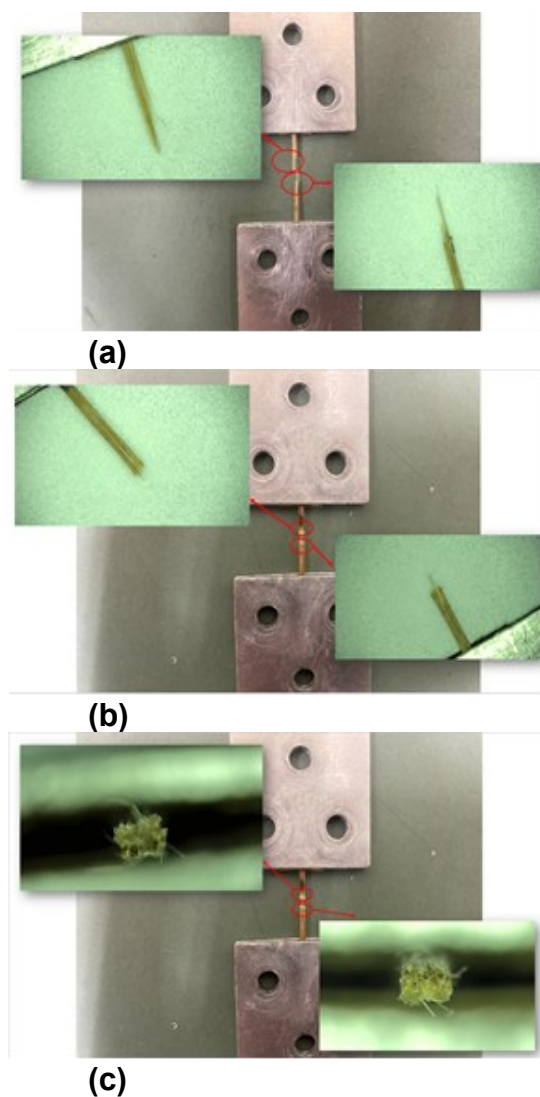


Fig. 13. The fracture manner of the (a) original bamboo fiber, (b) angle-shaped bamboo fiber, and (c) the cross section of the angle-shaped bamboo fiber

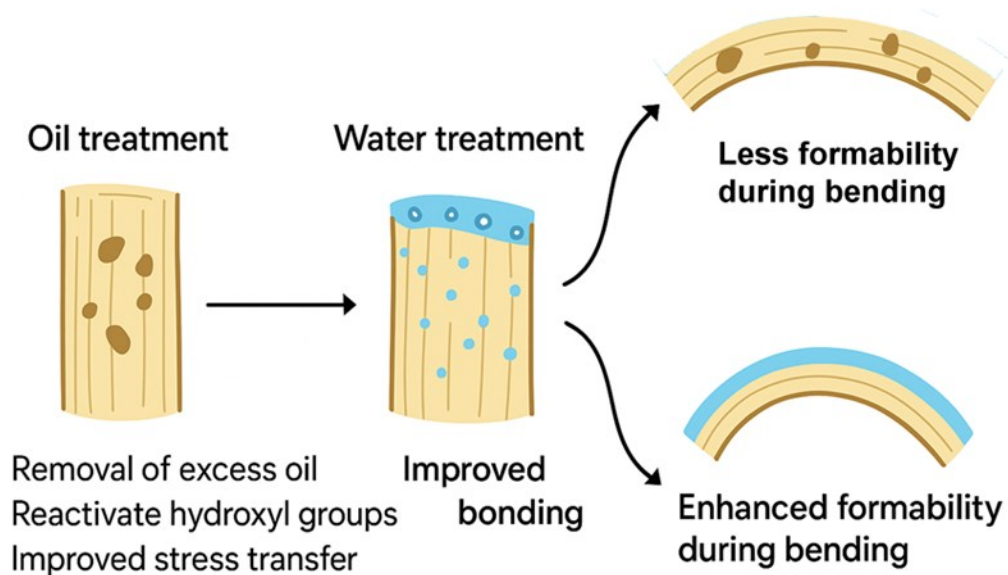


Fig. 14. Sequential effects: oil treatment, water treatment, and improved epoxy bonding and bending formability

Effects of Preforming Conditions

Building on earlier results, pre-treating bamboo fibers with oil and soaking them in water before preforming yielded the highest tensile strength. This section examines how various preforming conditions affected the tensile strength of angle-shaped bamboo fibers, all under the same surface treatment process. As shown in Fig. 15, AOWP represents the original preforming process. Increasing the preforming temperature to 140 °C (140VH) or pre-heating the bamboo fibers before preforming (120HV), both resulting in a reduction in the strength of the angle-shaped bamboo fiber. Moreover, employing a caul plate during preforming (120CP) had no impact on the strength of angled bamboo fibers.

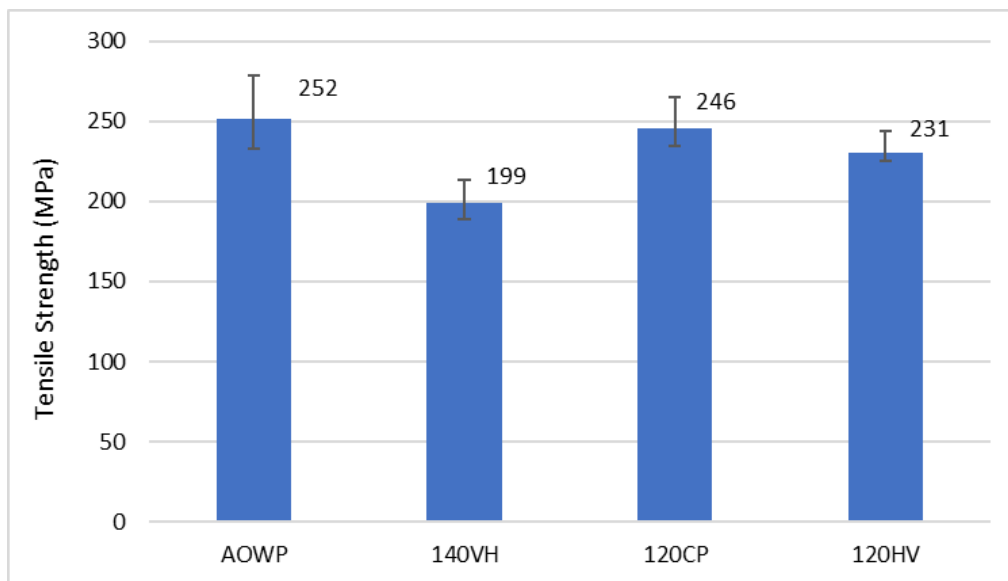


Fig. 15. Tensile strength of angle-shaped bamboo fiber by different preforming conditions

CONCLUSIONS

1. The study compared how different oil treatments affect moisture uptake, tensile performance, and interfacial shear strength of bamboo fibers with epoxy. Palm oil treatment at 150 °C emerged as the most effective, offering strong hydrophobicity and good bonding with epoxy. The chemical mechanism has been discussed by Marriam *et al.* (2024).
2. Palm oil likely outperforms the other oils because its composition, coating behavior, and compatibility with both bamboo fibers and epoxy provide a more uniform hydrophobic layer and stronger interfacial adhesion.
3. For bamboo fibers with a 0.7×1.0 mm² cross-section, every oil treatment reduced tensile strength, and higher treatment temperatures led to further decreases.
4. For angle-shaped bamboo fibers, replacing water soaking with oil treatment prior to preforming significantly lowered tensile strength. In contrast, if the fibers had been oil-treated first and then soaked in water before preforming, their strength increased.
5. Although palm oil treatment at 150 °C still reduced the intrinsic strength of straight bamboo fibers, it improved the tensile strength of angled bamboo fibers relative to specimens without oil treatment.
6. Results of this study supported surface treatment of bamboo fiber as a promising step for fabricating curved bamboo fiber composites. Curved bamboo composites can form dashboards, door panels, or seat frames, providing lightweight yet strong components with visually appealing surfaces. A curved bamboo panel in a car interior could reduce weight while maintaining structural rigidity.

ACKNOWLEDGEMENTS

The authors are thankful for the financial support from National Science and Technology Council in Taiwan under the contract of number of NSTC 112-2221-E-006-103-MY2.

Author Contributions

Pei-Chun Chen performed the experiments, analyzed the results and wrote the manuscript. Wen-Bin Young supervised the laboratory work, reviewed and edited the manuscript. The authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of Interest

The author states no conflict of interest.

Data Availability

Data will be made available on request.

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Article submitted: October 26, 2025; Peer review completed: November 15, 2025;
Revised version received: November 30, 2025; Accepted: January 19, 2026; Published:
April 9, 2026.

DOI: 10.15376/biores.21.2.4620-4642