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The Mechanical, Hygral, and Interfacial Strength of Continuous Bamboo Fiber Reinforced Epoxy Composites

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Abstract

This study is to investigate the mechanical, hygral, and interfacial strength of continuous bamboo fiber reinforced epoxy composites. The untreated and alkali-treated continuous bamboo fibers were prepared from cutting the nature bamboo culm. The basic characteristics of the bamboo fibers, such as density, equivalent diameter, and tensile properties were experimentally measured. The bamboo fiber reinforced epoxy (BF/EP) composites were fabricated by the resin transfer molding (RTM) process with the resulting fiber volume fraction about 42%. The strength of bamboo fiber was found to decrease with the alkaline treatment. However, alkali-treated bamboo fiber reinforced epoxy composites acquired better tensile strength than those with untreated bamboo fibers. The untreated bamboo fiber was believed to have weak interface with the epoxy resin, which was verified by the subsequent interface strength tests. The size effect of bamboo fibers on the tensile properties of the BF/EP composites were also studied. The results showed that the tensile strength and Young's modulus of the composite increase with the decrease of the bamboo fiber diameter. For the hygrothermal aging test, BF/EP composites are highly sensitive to moisture absorption, and the moisture has a detrimental effect on the mechanical properties of the BF/EP composite.

Keywords： bamboo fiber; bamboo fiber composite; alkali treatment; interface shear stress

1. Introduction

Fiber Reinforced Polymer (FRP) is the most widely used composite. According to literature, glass fiber reinforced composites began mass production in the industry in the 1940s. Later, the advent of carbon fiber reinforced composites played an important role in defense and aerospace industry. In recent years, environmental awareness has emerged, and fossil fuels have gradually become depleted at the same time [1]. The commonly used synthetic fibers such as carbon fiber and glass fiber are not easily decomposed in the natural environment and subjected to the problem of environmental pollution. As a result, the development of green composites and biodegradable materials has attracted much attention. In the 2010s, about 315,000 tons of natural fibers were made into composites, which accounted for 13% of the total reinforcing materials which include glass fiber, carbon fiber and natural fiber. It is estimated that by 2020s it will increase to about 830,000 tons [2, 3]. In the field of natural fiber reinforcement, a large number of plant fiber reinforced polymer composites have been used in the past years. Commonly used plant fibers include bananas, sisal, cotton, bamboo, and wood [4-8]. These plant fibers have the advantages of low density, good thermal insulation and mechanical properties, low cost, durability, sustainability and biodegradability [9-11].

Bamboo is a suitable choice for the development of natural fiber composites. It grows rapidly, up to several centimeters per day, and has excellent mechanical properties [12]. There were numerous bamboo fiber extraction methods such as retting, steam explosion, alkali treatment, and degumming, etc. [13-16]. All the extraction methods will directly affect the quality and strength of the fibers.

Bamboo is a natural honeycomb fiber-reinforced composite material. Vascular Bundles are surrounded by parenchyma cells. The vascular bundle consists of vessels, a phloem, and a large number of fibers. Parenchyma cells is a lignified wall composed of lignin, cellulose and hemicellulose. In the entire bamboo stalk, fiber and parenchyma occupy 40% and 50% respectively [17]. The cell structure of fiber in the vascular bundle has a small hole in the middle, which is surrounded by a multi-layer structure consisting of a secondary wall and a primary wall from the inside to the outside. These cell walls consist of cellulose, hemicellulose, polysaccharides and pentose sugars. There is also an intermediate layer outside the primary wall between fibers. There is also an intermediate layer outside the primary wall between vascular bundles. The main component of this layer is lignin with the content of more than 90% [18]. The cell wall structure and mechanical properties of bamboo fibers were studied using scanning electron microscopy (SEM), atomic force microscopy (AFM), and nano indentation by Zou et al [19, 20]. The investigation showed that the bamboo fiber cell wall is composed of cobblestone-like nano-sized polygonal cellulose particles, approximately 21-198 nm in size. For the bamboo fiber with a nano-grain structure, the measured hardness is 0.44±0.09 GPa and the elastic modulus is 10.4±1.8 GPa. The cellulose, lignin and hemicellulose account for about 95% of the plant cell wall [21]. Although lignin has the function of binding fibers together, it is a complex compound that causes poor interfacial adhesion with polymer resin [22, 23]. However, lignin can be dissolved in sodium hydroxide solution [24] during the fiber extraction process. The experimental results showed that proper surface treatment could effectively remove lignin and hemicellulose [25, 26], resulting in a better interface than those obtained without the alkaline treatment [27-30].

In use, composites are often exposed to moisture. When the composite absorbs moisture, the water and the polymer interact (hydrolyze) or affect the adhesion between the matrix and the fiber, leads to a hygrothermal aging of the composite which has a detrimental effect on the mechanical properties of the composite [31-33]. Unlike glass fibers, the prominent tendency of natural fibers to absorb moisture is the biggest factor limiting biocomposites [24]. Therefore, it is important to study the phenomenon of bamboo fiber reinforced composites for hygrothermal aging.

This study is to investigate the mechanical, hygral, and interfacial strength of continuous bamboo fiber reinforced epoxy composites. The untreated and alkali-treated continuous bamboo fibers were prepared by cutting the nature bamboo culm. Bamboo fiber reinforced epoxy (BF/EP) composites were fabricated by using the resin transfer molding (RTM) process. The size effect of bamboo fibers on the tensile properties of the BF/EP composites and hydrothermal aging test were also studied.

2. Experiment

2.1 Extraction of Continuous Bamboo Fiber

To mechanically extracting bamboo fibers, a bamboo culm section was cut without node portions first and barks were removed from the bamboo culm. Secondly, the bamboo culm was cut into thin bamboo strips, and further divided them to thin fibers. Noticed that the bamboo fibers used in this study had a dimension about 0.7×0.7×160 mm and its inner structure contained fibers, parenchyma cells, vessels and phloem. Then, BF were placed in an oven with the temperature of 80 °C for 5 hours to remove the contained moisture. Finally, the average volume of a bamboo fiber was measured, which was used to calculate the equivalent diameter and density.

2.2 Alkaline treatment

Alkaline treatment of bamboo fiber was performed by submerging and boiling BF in the sodium hydroxide solution (concentration: 0.1 N) in a pot at 100°C for 12 hours. After that, alkali-treated bamboo fibers (ALK-BF) were washed with distilled water, and then were placed in an oven to dry out under the temperature of 80°C for 8 hours. The average volume of a single bamboo fiber was also measured to calculate the equivalent diameter and density of ALK-BF.

2.3 BF/EP composites

Bamboo fiber reinforced epoxy composites were fabricated by using the resin transfer molding process. Before RTM, the resin (ML 3564, Golden Gate Chemical, Taiwan) and hardener (HY 3954, Golden Gate Chemical, Taiwan) were placed in the degassing equipment to eliminate dissolved air for 6 hours. Then, the resin and hardener were mixed in a beaker at a weight ratio of 100:35. After that, the mixed resin were poured into a pressure cylinder. For RTM process, the bamboo fibers (BF or ALK-BF) were manually placed in the mold cavity (160x130x1.5 mm) with an aligned direction. The regulated high pressure nitrogen was connected to the pressure cylinder to force the resin into the mold cavity while the mold was mounted on a hot press. After the injection process, the curing was performed at 140 □ for 2 hours. The resulting BF/EP and ALK-BF/EP composites had the fiber volume fraction about 42%. Those composites were considered as quasi-unidirectional because the manually placed fibers were not perfectly aligned. The theoretical density of the composite could be estimated using the formula of rule-of-mixture. The density was also measured experimentally to compare with the theoretical values.

2.4 Tensile test of bamboo fiber

Before the tensile test, the BF and ALK-BF were attached on a paper with epoxy adhesive, as shown in Figure 1. Then, samples were dried at 80°C for 5 hours to cure the epoxy adhesive and further dry the fiber. Finally, the tensile strength of both fibers was measured using a micro-stretcher.

2.5 Tensile and bending test of BF/EP composites

Tensile and bending tests of composites were performed using a universal material testing machine (250 kN capacity). Three points bending tests were performed to measure flexural strength with a bending span of 100 mm. BF/EP composite was cut into a strip specimen with 160×12×1.84 mm or 160×10×1.84 mm, respectively, for tensile or bending test. For tensile test specimen, both ends are attached with end tabs to prevent specimen damage from the clamp. Before testing, all the specimens were placed in an oven at a temperature of 80 °C for 8 hours to remove moisture. Both BF/EP and ALK-BF/EP composites were used for tensile and bending tests.

For unidirectional composites, the Young’s modulus along the fiber direction can be properly estimated by the rule of mixture which are written as follows:

$$E_c = E_f V_f + E_m V_m \tag{1}$$

where E_c is the Young's modulus of the composite along the fiber direction, E_f is the Young's modulus of the fiber, E_m is the Young's modulus of the matrix, V_f is fiber volume fraction, and V_m is matrix volume fraction.

For the analysis of composite strength, if the matrix failure strain is greater than the fiber failure strain, the longitudinal tensile strength of the continuous fiber composite laminate can be estimated using the micromechanical model reported by Kelly and Davies [34]. This model in equation 2 can be used to calculate the tensile strength of the BF/EP composite in the fiber direction, and compared with the experimental results.

$$S_L^{(+)} = S_{f1}^{(+)} V_f + S_{mf1}^{(+)} (1- V_f) \tag{2}$$

where $S_L^{(+)}$ is the tensile strength of composite in fiber direction, $S_{f1}^{(+)}$ is the tensile strength of fiber, $S_{mf1}^{(+)}$ is the strain at the time of fracture of the fiber corresponding to the stress value on the oblique line of the matrix, V_f is fiber volume fraction, as shown in Figure 2.

2.6 Measurement of Interface shear stress

The pull-out test was used to measure the interfacial shear stress between bamboo fiber and epoxy resin. First, the bamboo fiber is embedded into the uncured resin with the appropriate depth, as shown in Figure 3(a). A homemade pull-out test stand shown in Figure 3(b) was used for the measurement. The sample was fixed on the stand and the pull-out displacement was applied by a wheel handle with a rate about 0.15 mm /min. The loading force during the pulling was read out by a force sensor at the same time. After the resin was solidified, the single fiber was pulled out from the epoxy resin, and the pull-out load was recorded. The resulted average interfacial shear stress was calculated using the equation indicated by Greszczuk [35] as:

$$\tau = F/\pi\, d\, L \tag{3}$$

where τ is the interfacial shear stress, F is the pull-out load, d is the fiber diameter, and L is the depth of the fiber embedded in the matrix.

2.7 Effect of the bamboo fiber diameter

The purpose of this experiment was to understand the effect of the bamboo fiber diameter on the strength of the ALK-BF/EP composites. First, cut three batches of bamboo fibers each having a length of 160 mm and a cross section in dimensions of approximately 0.9×0.9 mm, 0.7×0.7 mm, and 0.5×0.5 mm, respectively. All the bamboo fiber samples in this case were alkali treated (concentration: 0.1 N sodium hydroxide solution, temperature: 100°C, time: 12 hours). Secondly, the average volume of ALK-BF were measured, which were used to calculate the equivalent diameter. Then, specimens of ALK-BF/EP composite were made by RTM also. All the specimen have a fiber volume ratio of 42%. Finally, tensile testing was conducted for those specimens to measure their strength.

2.8 hygrothermal aging tests

The purpose of this experiment was to discuss the moisture absorption capacity of bamboo fiber composites and the effect of heat and humidity on the mechanical properties. First, Specimens of ALK-BF/EP composite with fiber volume fraction about 42% were prepared by RTM. Next, all specimens were oven dried to eliminate all the humidity. Then, the composite specimens were immersed in water at 100 °C for different times of 1 hour, 2 hours, 3 hours, and 4 hours, respectively. In order to evaluate the weight change of the composite after water absorption, the weight of dry specimen, W_0, and the weight after water absorption, W_1, were measured for each specimen. The following equation was used to calculate the moisture content, W_c, of a composite:

$$W_c = (W_1 - W_0)/W_0 \tag{4}$$

To investigate the changes in the mechanical properties of composites under hot and humid conditions, the specimens were subjected to both the tensile and three-point bending tests after hygrothermal aging.

3. Results and Discussions

3.1 The basic characteristics of the bamboo fibers and bamboo fiber composites

The basic characteristics of the bamboo fibers from the test results are given in Table 1. After the alkaline treatment, the average density of BF increased from 0.93 g/cm^3 to 1.29 g/cm^3 and the average equivalent diameter decreased from 643.15 mm to 583.80 mm. For the tensile tests of a single bamboo fiber, typical stress and train curves are given in Figure 4. The results are also listed in Table 1. As comparison of the alkali-treated and untreated bamboo fibers, the average tensile strength decreased from 717.53 MPa to 473.05 MPa, and Young's modulus decreased from 43.34 GPa to 33.31 GPa. Noticeable decrease of mechanical properties were observed for the bamboo fibers after alkaline treatment. As composed to the BF/EP composite, the ALK-BF/EP has higher tensile strength due to the better interface shear strength although the ALK-BF tensile strength is weaker. The interface shear strength between the fiber and epoxy will be discussed later.

Figure 5 shows the fiber structure of BF and ALK-BF taken by a Dual-Beam Focused Ion Beam microscope. For untreated bamboo fibers in figures 5(a) and 5(b), it was observed that the BF retains the intact vascular bundle, and the fibers in the vascular bundle also retain the complete hexagonal structure. The figure5 (c) showed the structure of the ALK-BF where the vessels, phloem, and parenchyma cells were removed by the alkali treatment. In a higher magnification view, the figure 5(d) showed that the lignin between fibers was dissolved by alkali, resulting in gaps between the fibers. This explains why the tensile strength of bamboo fibers decreases after alkali treatment.

The densities of the bamboo fibers composites are given in Table 2. Theoretical estimations of the composite density with rule of mixture were also listed in the table. As compared to the measured results, the theoretical estimations can give reasonable predictions. The ALK-BF/EP composite has a higher density than BF/EP composites because the BF after alkaline treatment has higher density. Furthermore, the deviation of densities of BF/EP composites is higher than that of ALK-BF/EP composites because the BF contains a lot of lignin, pectin and impurities. Figure 6 shows the photographs of finished continuous unidirectional bamboo fiber composites for BF/EP and ALK-BF/EP.

3.2 Tensile and bending test of BF/EP composites

Figure 7 shows the tensile strength and modulus of the epoxy (EP), BF/EP composite, and ALK-BF/EP composite. For the neat epoxy, the tensile strength is 79 MPa and the Young's modulus is 2.5 GPa. With the BF/EP composites, the tensile strength in the fiber direction increased to 168.87 MPa and the Young's modulus increased to 8.54 GPa, showing successful reinforcing effect of the bamboo fibers. After BF was treated by alkali, the tensile strength of the ALK-BF/EP composite in the fiber direction increased to 222.71 MPa, and the Young's modulus increased to 13.10 GPa. Almost 30% and 40% increases in tensile strength and modulus were noticed for the alkali-treated BF composites.

The flexural strength and modulus were shown in Figure 8 from three-point bending tests. The results shows the same trend as the alkali-treated BF having better reinforcing effect for the composites. The resulting flexural strength of EP/BF composite is 141.39 MPa and the flexural modulus is 10.09 GPa. After BF was treated by alkali, the flexural strength of the composites increased to 182.29 MPa and the flexural modulus increased to 17.23 GPa.

From the test results of a single bamboo fiber, the tensile strength and modulus of ALK-BF are smaller than those of BF. On the other hand, ALK-BF composites have larger strength and modulus than BF/EP composites. Based on equations 1 and 2, the tensile strength and modulus of composites in the longitudinal direction can also be calculated theoretically. The results for both the theoretical and experimental results are listed in Table 3. It was found that the experimental values of tensile strength and modulus of the ALK-BF/EP composite were closer to the theoretical values. The BF/EP composite showed different results with the experimental values far below the theoretical predictions. It was believed that the untreated BF has poor interface adhesion with the epoxy. The derivations of equations 1 and 2 assumed a perfect interface between the matrix and reinforcement. Under this circumstance, equations 1 and 2 may not hold for the BF/EP composites. That explains the reason of poor predictions of tensile strength and modulus for BF/EP composites.

In order to further investigate the interface adhesion between BF and epoxy, the fracture surface of the specimen after the tensile test was observed using an optical microscope, as shown in Figure 9. A fiber pullout behavior was found at the fracture surface for BF/EP composites, indicating poor interface adhesion between the BF and epoxy. For ALK-BF/EP composites, the fracture surface being quite smooth without any fiber pullout implied good interface adhesion. This might explains the better mechanical properties found in ALK-BF/EP composites.

3.3 Fiber pullout test

A direct fiber pullout test was conducted to confirm the conclusions derived from the previous discussion about the interface adhesion between BF and epoxy. The measured average interface shear strengths from fiber pullout tests are shown in Figure 10. The ALK-BF has higher interface shear strength with the epoxy as compared to untreated BF. It was also noticed that the measured shear strengths of the ALK-BF had larger scattering, which might be caused by uneven alkali washing of the bamboo fiber through the alkaline treatment process. From the above results, it was confirmed that the interfacial adhesion between the ALK-BF and the epoxy resin was better, resulting in a stronger reinforcing effect in composites.

3.4 Effect of the bamboo fiber diameter

In this experiment, under the same alkaline conditions (concentration: 0.1 N sodium hydroxide solution, temperature: 100° C., time: 12 hours), three batches of ALK-BF each having a length of 160 mm and average equivalent diameter of 719.33 μm , 583.80 μm and 340.76 μm were obtained, respectively. Then, specimens of ALK-BF/EP composite were made by RTM also. Table 4 shows the tensile strength and modulus of ALK-BF/EP composites with different bamboo fiber diameters. For fiber diameters of 719.33 μm and 583.80 μm, the tensile strength and modulus have slight increase for smaller fiber diameter. However, due to the large deviation, the increase trend is not so obvious. For composites made from smaller fiber diameter of 340.76μm, the tensile strength and modulus increase significantly as compared to the composites with larger fiber diameter.

3.5 Hygrothermal aging test

The moisture absorption of ALK-BF/EP composites and neat epoxy was shown in Figure 11 for different soaking time in boiling water. There is no obvious moisture absorption for neat epoxy. However, with the adding of ALK-BF in the composites, the moisture absorption behavior is apparent. The moisture content of ALK-BF/EP composite increases quickly with the duration of soaking in boiling water. For about 4 hours, the moisture content of the ALK-BF/EP composite reaches the saturation about 19%.

The tensile and three-point bending tests were also conducted for ALK-BF/EP composite after hygrothermal aging. Figure 12 shows the results of tensile and bending tests. It was found that the mechanical strength and modulus of ALK-BF/EP composites decreased with the increase of moisture content. With 1 hour duration of hygrothermal aging, the strength may lose 25% of the original value. As the moisture reaching saturation, the composites may only retain 50% of the original strength. The results show that the hygrothermal aging has a detrimental effect on the mechanical properties of the bamboo fiber composites.

4. Conclusions

This study successfully used resin transfer molding to fabricate continuous unidirectional bamboo fiber reinforced epoxy composites. Some conclusions may be drawn from above discussions.

1. Compare to BF, the ALK-BF has a larger density because some lignin, hemicellulose, fructose, and impurities are removed in the alkaline treatment. On the other hand, the tensile strength and modulus of bamboo fibers decrease after alkaline treatment. As compared the data from literature, Figure 13 shows the strength of the bamboo fiber extracted by different methods [36]. Our study shown in solid circles have the comparable results. The mechanically extracted BF has the better strength compared to other methods.
2. The addition of continuous BF in the epoxy resin results in a composite with good reinforcing effect as compared to the short BF reinforced composites. The ALK-BF/EP composite has higher tensile strength and modulus than BF/EP composite. The flexural strength and modulus also show the same conclusion. This implies that the alkali-treated bamboo fibers have better efficiency as reinforcement in composites. Figure 14 shows the strength of different BF/epoxy composites from literatures [37-39]. Our results shown in A and G for ABF/EP and BF/EP composites. Jain's results as shown in B [39] had untreated bamboo fiber, which had similar strength as ours. Kushwaha' results in C and H [38] were the strengths of bi-directional BF/EP composites, having a lowere strength compared to the unidirectional composites. Banga's results in D, E, and F [37] were the strengths of short BF composites that had lower strength.
3. Through the optical microscopy and pull-out test, it was found that the interface between BF and epoxy resin was poor, but the interfacial adhesion could be improved by alkaline treatment.
4. Under the condition of constant bamboo fiber length, the tensile strength and Young's modulus of bamboo fiber composites increase with the decrease of bamboo fiber diameter.
5. Bamboo fiber composites are highly sensitive to moisture absorption, and the hygrothermal

aging has a detrimental effect on the mechanical properties of the bamboo fiber composites.

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Table 1. The basic characteristics of bamboo fiber

	Density (g/cm^3)	Equivalent diameter (μm)	Tensile strength (MPa)	Elongation at break (%)	Young's Modulus (GPa)
BF	$0.93^{+0.06}_{-0.04}$	$643.15^{+81.00}_{-66.15}$	$717.53^{+176.87}_{-188.67}$	$2.03^{+0.56}_{-0.38}$	$43.34^{+8.66}_{-8.55}$
ALK-BF	$1.29^{+0.05}_{-0.07}$	$583.80^{+38.20}_{-33.93}$	$473.05^{+101.12}_{-52.63}$	$2.05^{+0.53}_{-0.39}$	$33.31^{+3.09}_{-1.92}$

Table 2. Density of bamboo fiber Composites

	Fiber volume fraction (%)	Theoretical density (g/cm^3)	Measured density (g/cm^3)
BF/EP composites	42	$1.04^{+0.02}_{-0.02}$	$1.08^{+0.12}_{-0.09}$
ALK-BF/EP composites	42	$1.19^{+0.02}_{-0.03}$	$1.16^{+0.02}_{-0.01}$

Table 3. Comparison of theoretical and experimental values of tensile properties

	BF/EP composites		ALK-BF/EP composites	
	Tensile strength (MPa)	Young's modulus (GPa)	Tensile strength (MPa)	Young's modulus (GPa)
Theoretical value	$315.86^{+76.9}_{-83.86}$	$19.65^{+3.64}_{-3.59}$	$213.18^{+45.08}_{-18.91}$	$15.44^{+1.30}_{-0.81}$
Experimental value	$167.87^{+13.05}_{-25.01}$	$8.54^{+2.25}_{-0.98}$	$222.71^{+15.52}_{-21.30}$	$13.10^{+1.36}_{-1.65}$

Table 4. Tensile properties of ALK-BF/EP composites with different fiber aspect ratios

Average of equivalent diameter (μm)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation (%)
$719.33^{+14.31}_{-15.46}$	$213.47^{+11.27}_{-7.15}$	$11.96^{+0.41}_{-0.87}$	$1.76^{+0.13}_{-0.16}$
$583.80^{+38.20}_{-33.93}$	$222.71^{+15.52}_{-21.30}$	$13.10^{+1.36}_{-1.65}$	$2.01^{+0.14}_{-0.19}$
$340.76^{+98.00}_{-25.53}$	$269.05^{+22.62}_{-20.43}$	$16.43^{+1.59}_{-1.38}$	$2.23^{+0.27}_{-0.31}$

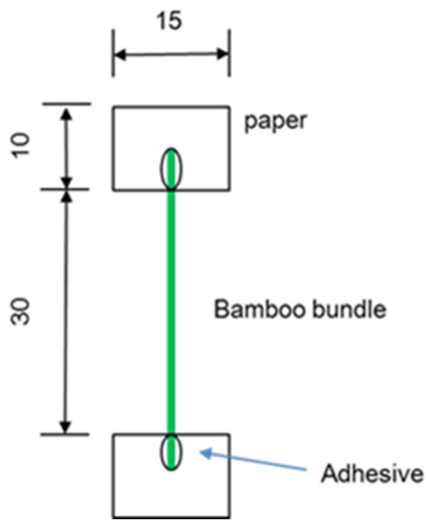


Figure 1 Tensile specimen of a single fiber

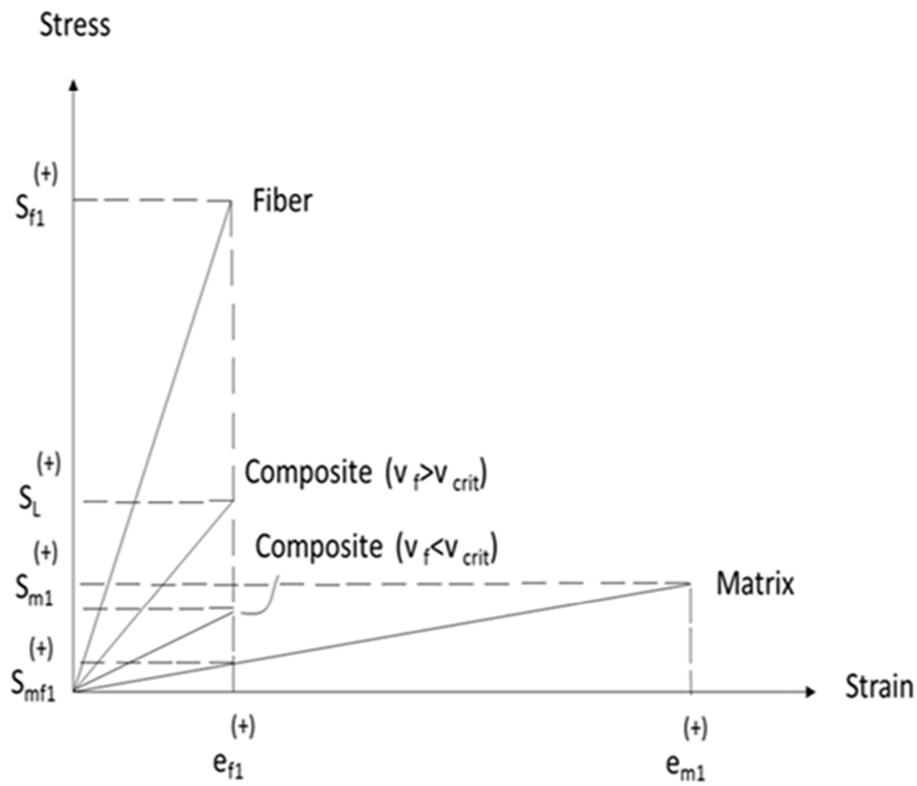
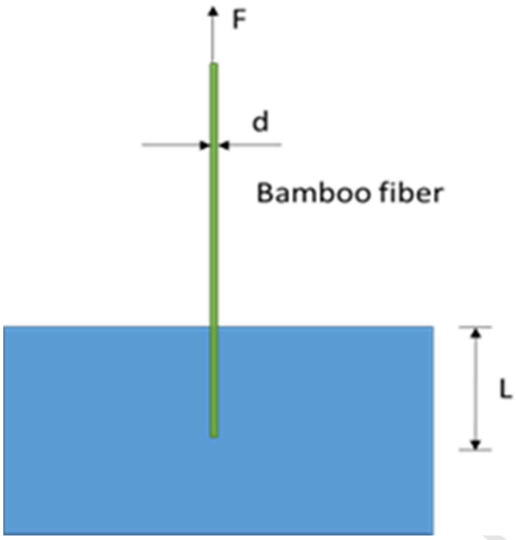
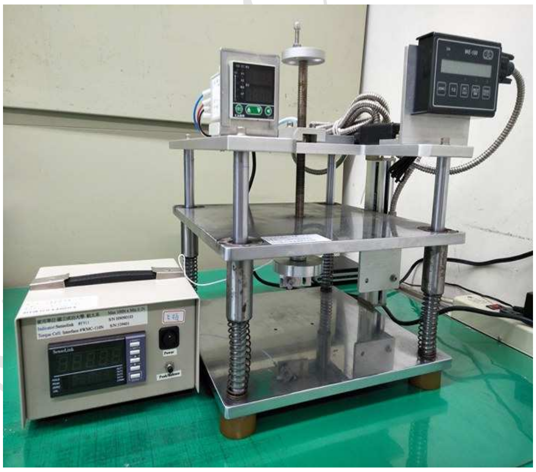


Figure 2 Micromechanical model of longitudinal strength of composite [34]

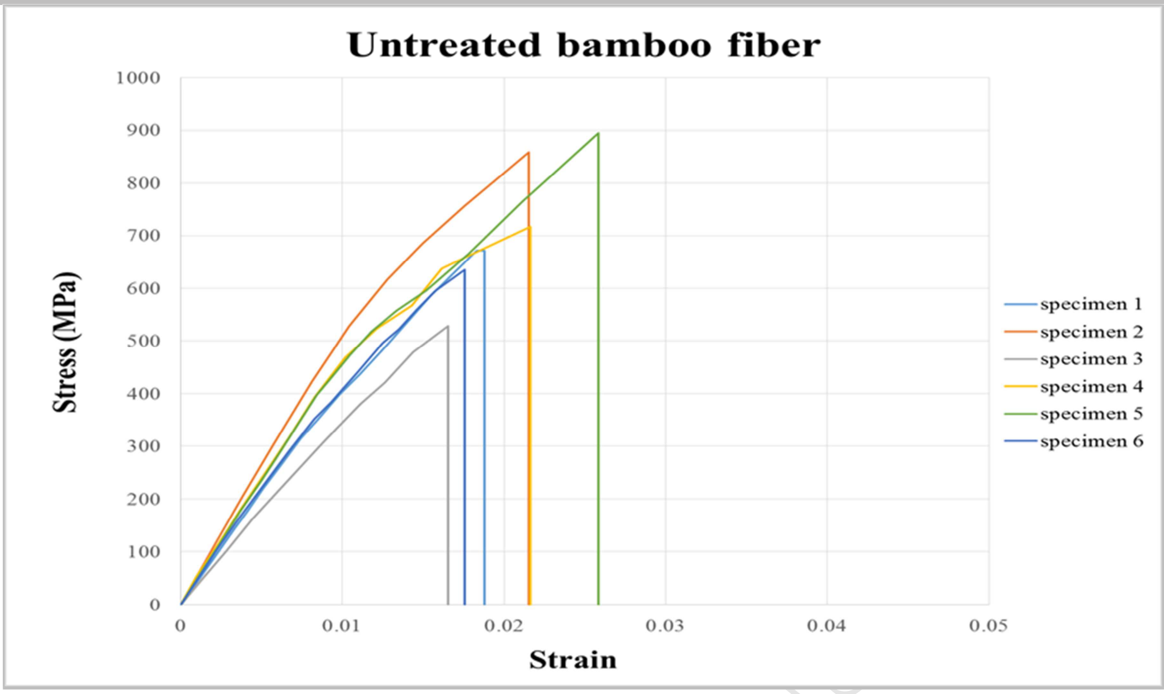


(a)

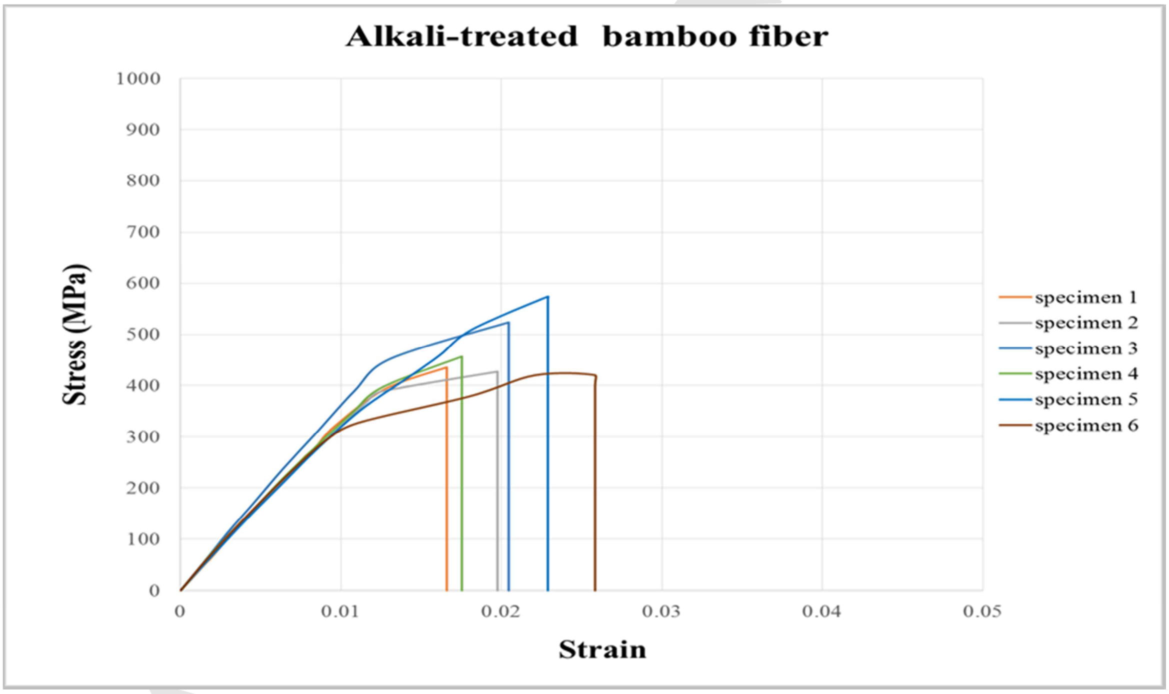


(b)

Figure 3 Pull-out test method of a single fiber (a) the sample setup (b) pull-out test stand



(a)



(b)

Figure 4 (a) typical stress strain curves for untreated bamboo fiber tensile tests (b) typical stress strain curves for alkali-treated bamboo fiber

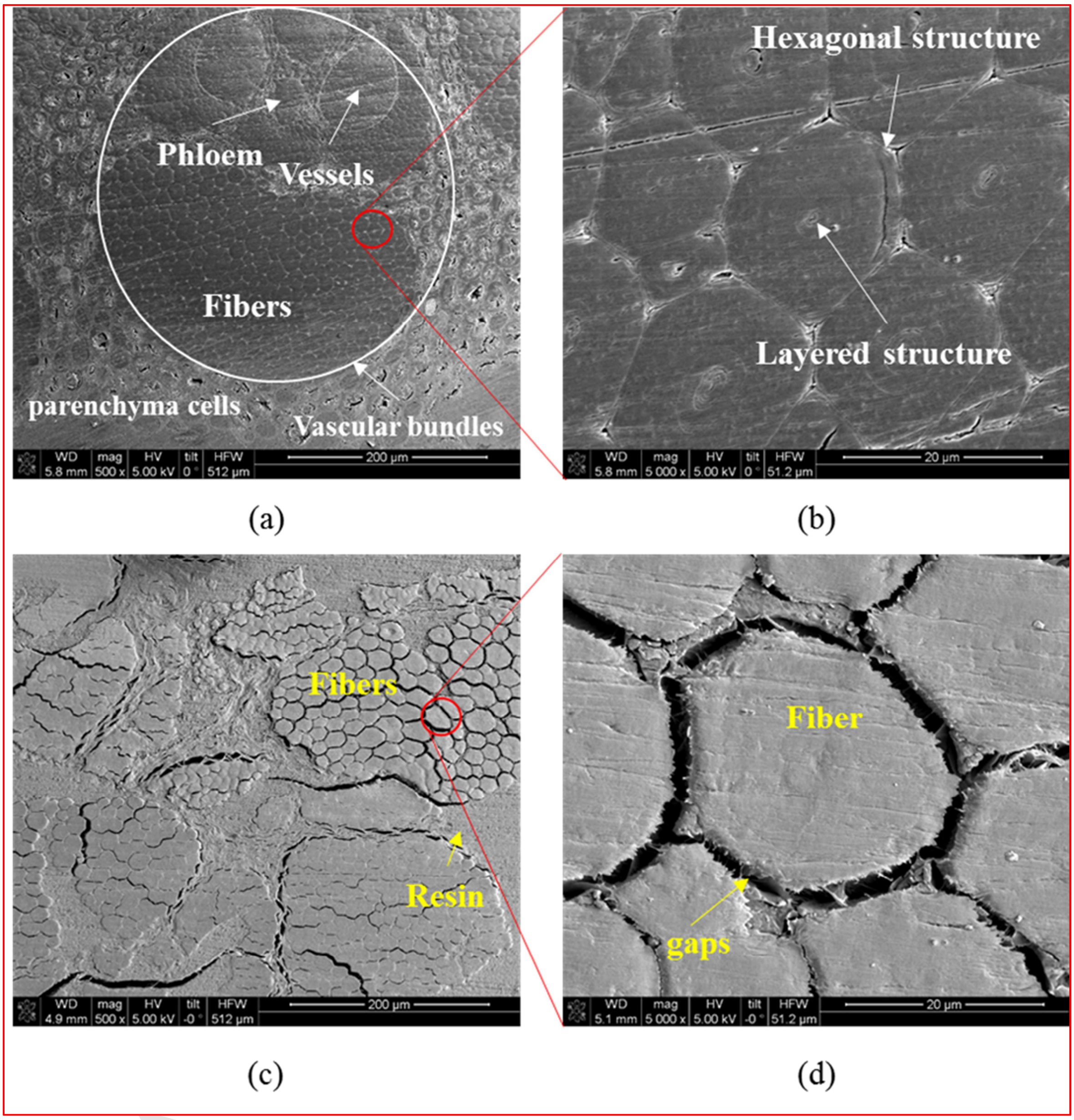


Figure 5 (a) observation of BF cross section at 500x magnification (b) observation of BF cross section at 5000x magnification (c) observation of ALK-BF cross section at 500x magnification (d) observation of ALK-BF cross section at 5000x magnification

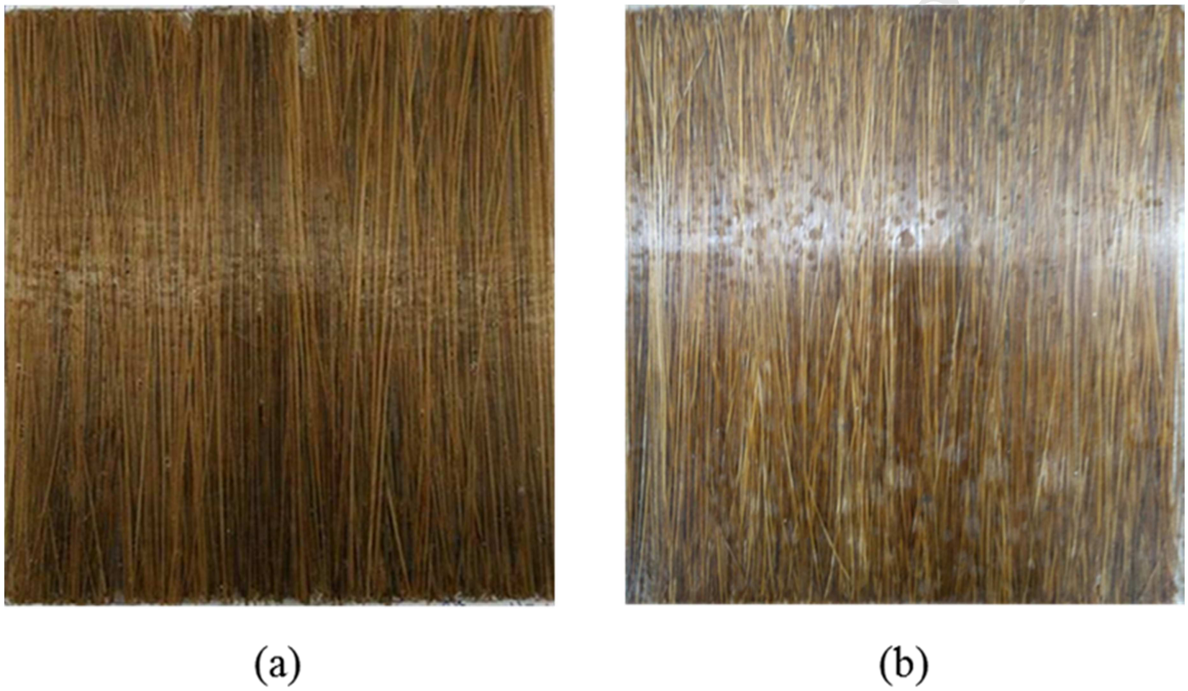


Figure 6 (a) untreated bamboo fiber/epoxy (BF/EP) composite (b) alkali-treated bamboo fiber/epoxy (ALK-BF/EP) composite

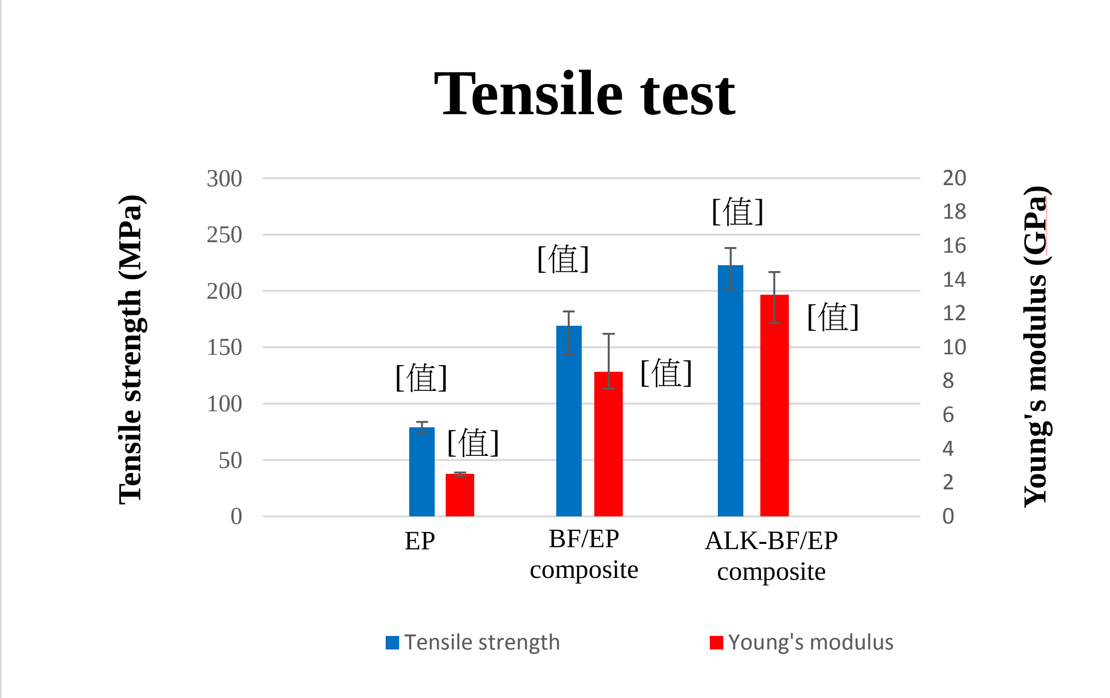


Figure7 Tensile strength and modulus of the epoxy (EP), bamboo fiber/epoxy (BF/EP) composite, and alkali-treated bamboo fiber/epoxy (ALK-BF/EP) composite

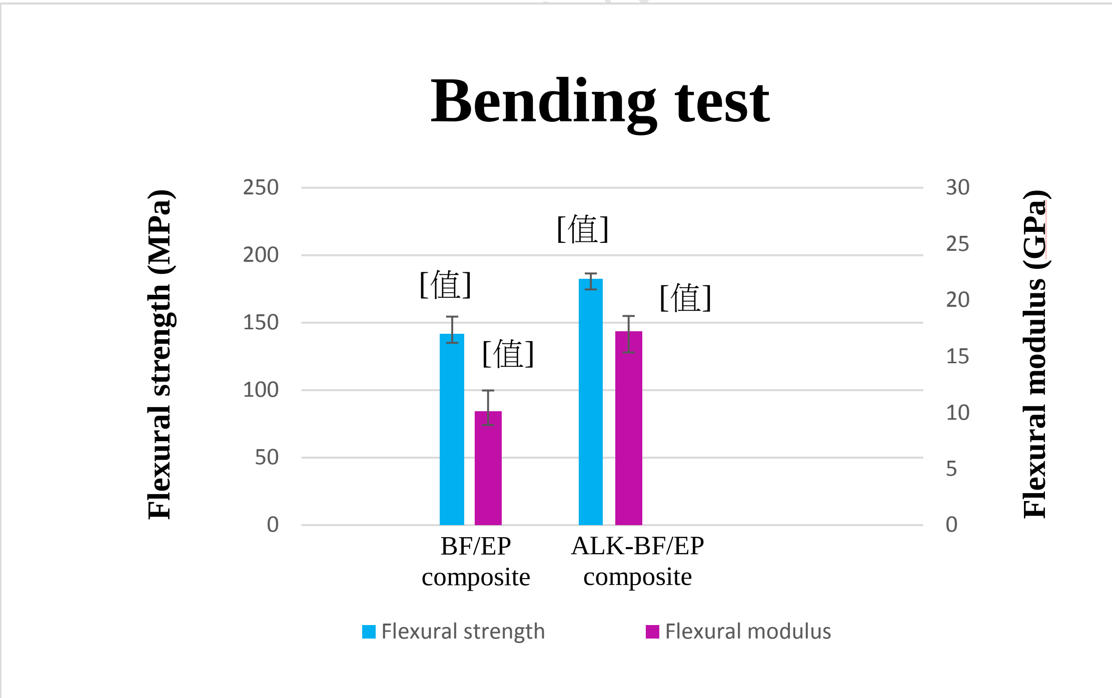
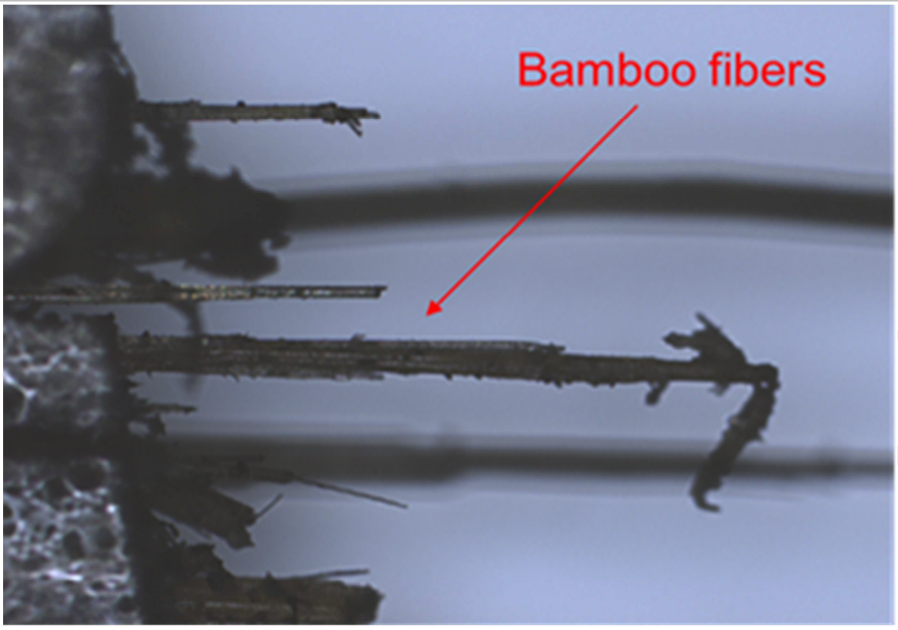
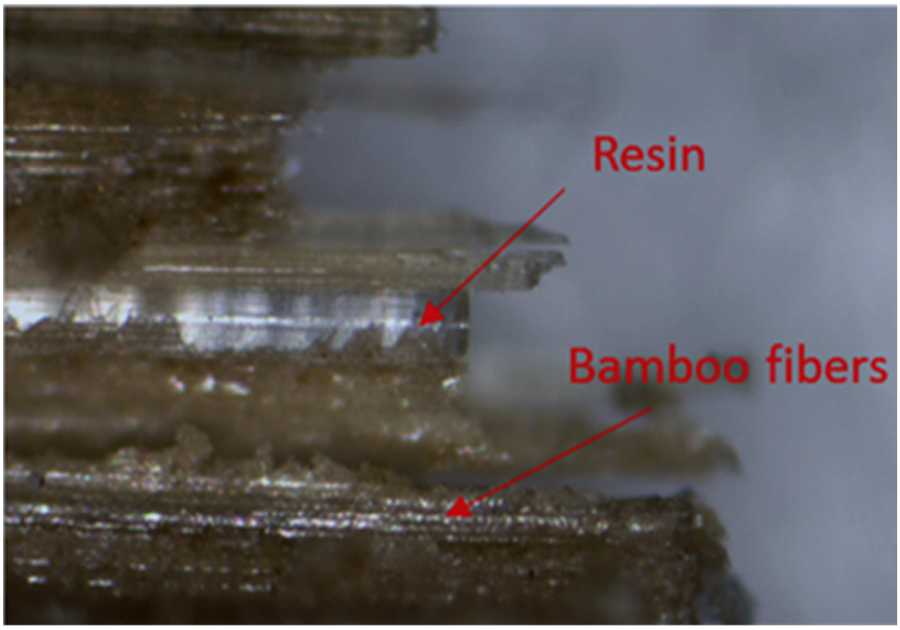


Figure 8 Flexural strength and modulus of bamboo fiber/epoxy (BF/EP) composite and alkali-treated bamboo fiber/epoxy (ALK-BF/EP) composite



(a)



(b)

Figure 9 Using the optical microscope to take fractures of tensile specimens: (a) epoxy /untreated bamboo fiber composite (b) epoxy/ alkali-treated bamboo fiber composite

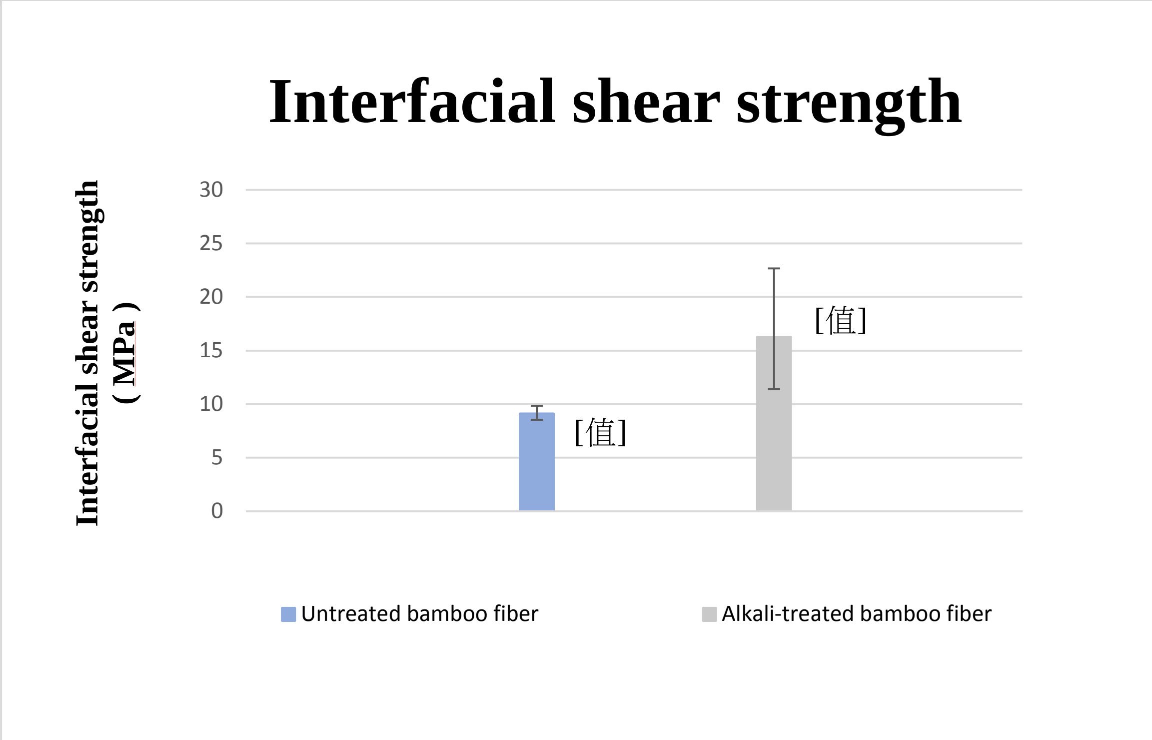


Figure 10 Average interfacial shear strength between bamboo fiber and epoxy resin

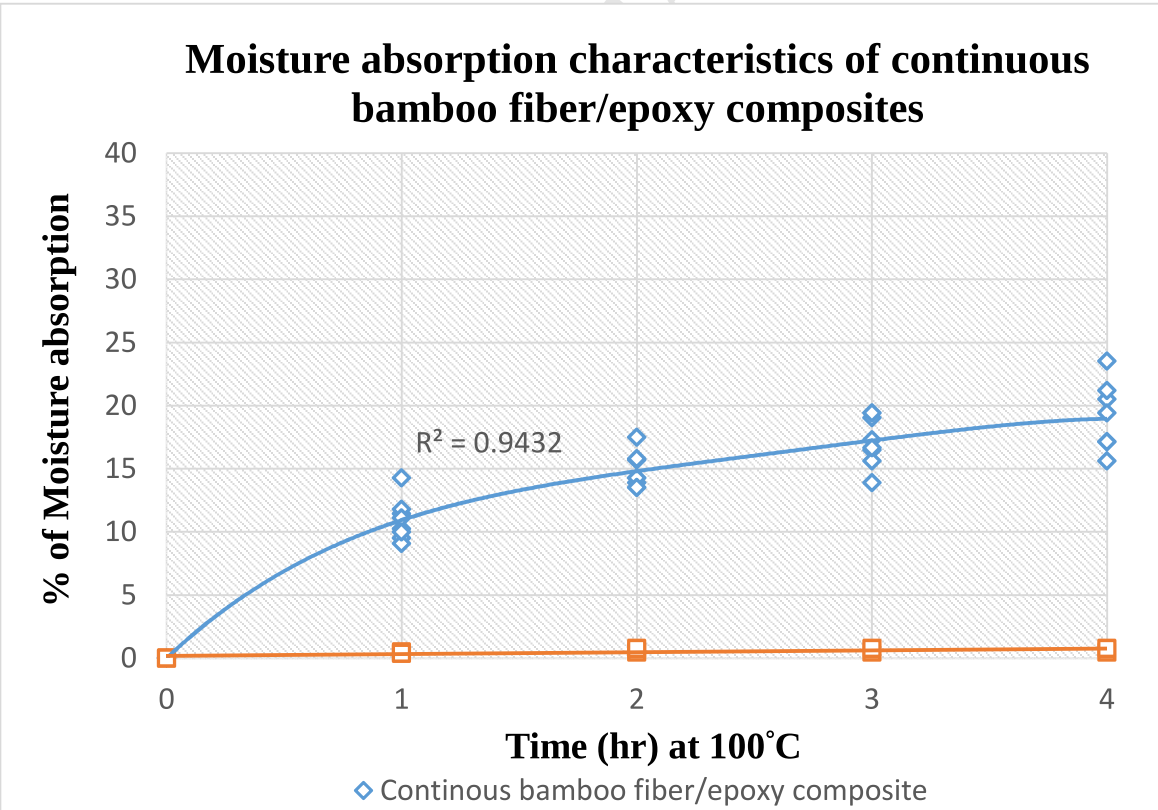


Figure11 Moisture absorption capacity of bamboo fiber composites

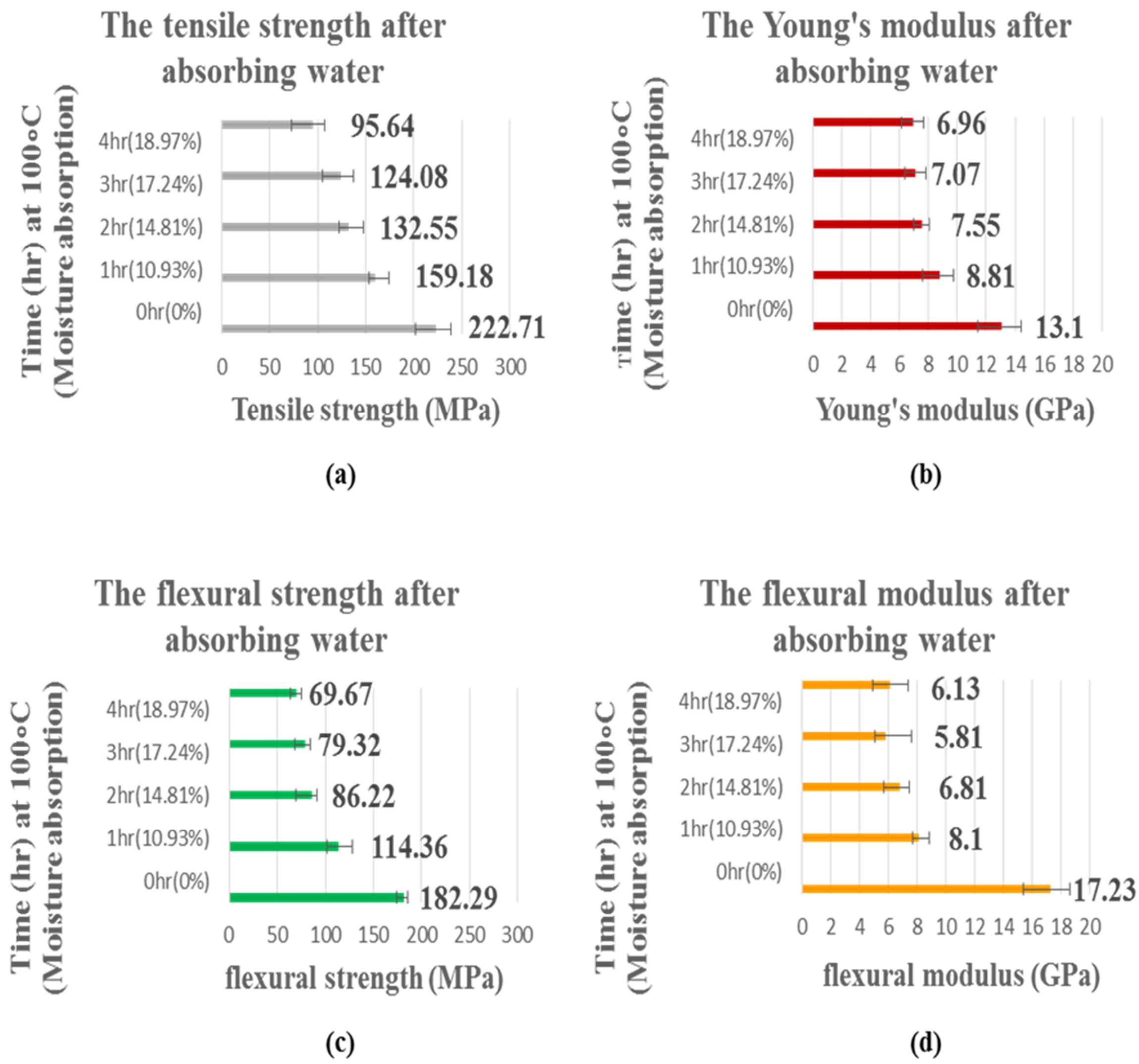


Figure 12 Changes in mechanical properties of bamboo fiber composites in a hot and humid environment, (a) tensile strength (b) Young's modulus (c) flexural strength (d) flexural modulus

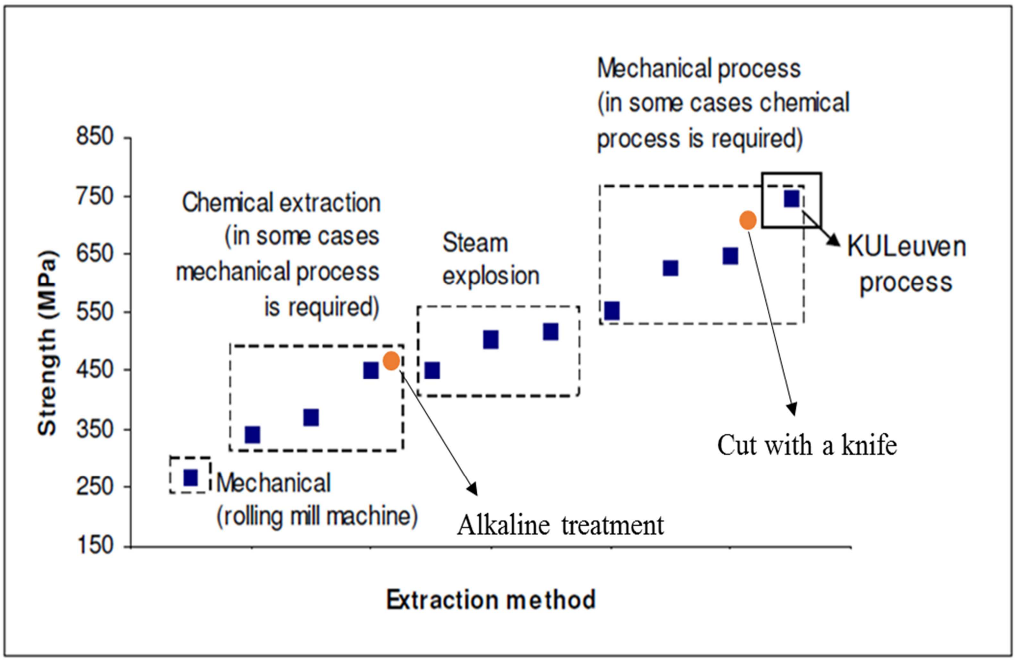


Figure 13 The strength of bamboo fibers extracted by different methods; our results shown in solid circles [36]

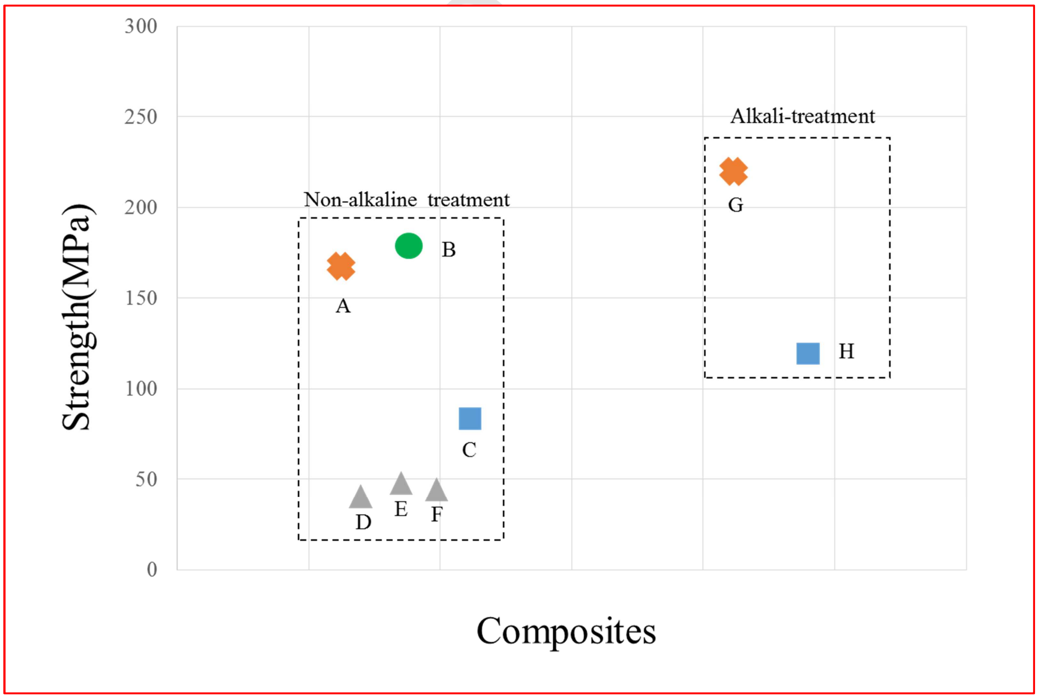


Figure 13 The strength of BF/EP composites; our results shown as A and G; Jain in B [39]; Kushwaha in C and H [38]; Banga in D, E, and F [37]