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The Effect of Morphology and Alkali Treatment of Bamboo on Tensile Properties of PLA/Bamboo Composites

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Abstract: Food packages and kitchen utensils made of thermoplastic are very popular due to their low production costs. However, thermoplastic is easily degraded at high temperatures and has low mechanical properties. When degraded, thermoplastic produces carcinogenic monomers that can contaminate food. Thus, natural fiber-based composites are introduced. Most commercial products nowadays are made of thermosets that are difficult to degrade. In order to produce fully biodegradable composite materials, we mixed PLA (polylactic acid) pellets with bamboo. PLA is a thermoplastic polyester that is synthesized from the fermentation of plant starch. The mechanical properties of PLA/bamboo composites depend on the surface interaction between PLA and bamboo. Thus, we studied the effect of the chemical treatment of bamboo prior to composite making on the mechanical properties of PLA and bamboo. Furthermore, the morphology of bamboo was varied into powder, fiber, and strip. A four-year-old bamboo trunk was harvested and dried to minimize the moisture content. Then, it is soaked separately in cold water and 5% NaOH for 72 hours. After it is rinsed and re-dried, the fiber and powder of bamboo are extracted through mechanical treatment. The composite is made with 10% bamboo reinforcement by hot press molding technology at 220°C for 40 minutes. The tensile testing shows that only bamboo strips can improve the mechanical properties of composites. Besides, the alkali treatment was found to increase the brittleness of bamboo, causing an increase in modulus elasticity and a decrease in ductility.

Keywords: Biodegradable Composite, Poly Lactide-Acid (PLA), Bamboo, Morphology, Alkali Treatment

1. Introduction

Thermoplastics such as polyethylene, polypropylene, and styrofoam have become the main choice for low-cost kitchen utensils and food packaging. However, when thermoplastics are exposed to high temperatures, the volatile compound poses a danger to the user. The monomers produced are carcinogenic and dangerous if they are mixed into the food consumed [1, 2]. Besides, thermoplastics are known to have low mechanical properties. Thus, utensils made of composite materials are introduced as they have better mechanical properties.

Polymer matrix composites are a mix between polymer as a matrix and reinforcement, which is in the form of powder or fiber. Composites that are made of thermoset matrix, such as epoxy/fiberglass and epoxy/carbon fiber, have been widely developed in industry to manufacture cars, airplanes, bicycles, ships, turbines, etc. Even though the tensile properties of these composites can compete with those of metal alloys, they are more brittle and require high production costs. Besides, thermoset plastic and synthetic fiber are difficult to naturally degrade and difficult to recycle [3]. Thus, it promotes the trash issue in the future. To tackle this challenge, a composite made of natural fiber and bioplastic is designed as an alternative material that is cheaper, biodegradable, and food-grade.

Previous research has tried to manufacture a natural-friendly composite made of pineapple, bamboo, and flax fiber [4]. Bamboo is one of the potential options due to its fast growth [5] and abundant availability. Bamboo belongs to the family Poaceae, with the subfamily

Babusodeae. There are 1450 species of bamboo around the world [6]. Bamboo can grow in low-nutrient soil [7]. Bamboo can be harvested after 3–5 years [8]. The availability of bamboo in Indonesia is abundant, with 14 million bamboo trunks per year [9]. The morphology of bamboo is separated into two parts: the rhizome and the trunk system. Bamboo has a straight, long shape and a hollow trunk with nodes [10]. Bamboo culm is composed of cellulose, hemicellulose, and lignin, which have distinct characteristics and consequently affect the mechanical properties of naked bamboo [11]. In terms of mechanical properties, bamboo has better ductility compared to slow-growth wood. However, the mechanical properties of bamboo can vary with the distance from the soil surface [12]. It is because there is a difference in the diameter and thickness of the bamboo culm. And it is also related to the differences in fiber bundle diameter that cause variations in tensile strength [13].

PLA is a thermoplastic consisting of the monomer lactide acid and can be produced from the fermentation of corn and potato starch [14]. PLA is considered environmentally friendly because it is relatively easy to degrade due to interaction with microbes, enzymes, and water through a hydrolysis reaction [15]. PLA is approved by the FDA (Food and Drug Administration) to be used for clinical purposes due to its biocompatibility [16]. PLA is available as a pellet or as an emulsion (resin). However, pure PLA is brittle and has low thermal resistance [17]. Combination of PLA with natural fiber results in an environmentally friendly composite, the so-called "Green Composite". Green composite is a type of composite that is made of renewable materials, notably agricultural and forestry products [18]. In composite PLA/bamboo, PLA acts as a matrix while bamboo acts as a reinforcement agent. Several studies have been done to investigate the tensile and flexural strengths of bamboo fiber with variations in the composition of bamboo fiber [19-21], the temperature of the hot press molding process [22], and the extrusion parameter process [23]. Meanwhile, for this research, we aim to vary the morphology of reinforcement and the pre-treatment of bamboo and then observe the influence on the mechanical properties of the composite.

2. Materials and Method

A four-year-old *betung* bamboo (*Dendrocalmus asper*) was harvested from the bamboo forest in Klungkung Regency, Bali. The bamboo culm used is at least 2 meters high at the soil surface, so the average culm thickness is 15–20 mm. Bamboo is then cut into 15–16 cm lengths. After that, it was sun-dried for 7 days to minimize the moisture content (MC), as MC affects the mechanical properties [24]. The surface modification of bamboo was done by soaking it in water and NaOH 5% separately for 72 hours. The soaking allowed the extractive compound to be dissolved in an aqueous environment. Then, the bamboo was sun-dried for 2 days and also dried in the oven at 60°C for 2 hours. The powder and fiber of bamboo were obtained through mechanical treatment. The bamboo powder was sieved to obtain a 40-mesh particle size, while the fiber has an average length of 10–15 mm. The bamboo strip was shaped to have dimensions of 150 x 25 x 5 mm (Figure 1).

PLA/bamboo composite was made with pellet thermoplastic PLA NV that has a processing temperature between 190°C and 250°C [25]. A hot press molding technique was used at 20 kPa pressure and 220°C for 40 minutes. The mixture of molten PLA and bamboo was pressed onto a tensile testing sample following ASTM D790. The amount of bamboo added was constant at 10 wt%. The mold was smeared with grease to ease the collection of the final product. The mechanical properties were investigated using a Universal Testing Machine (Tension) with a maximum load capacity of 5 kN. The tensile testing was done at a speed of 1 mm/min.

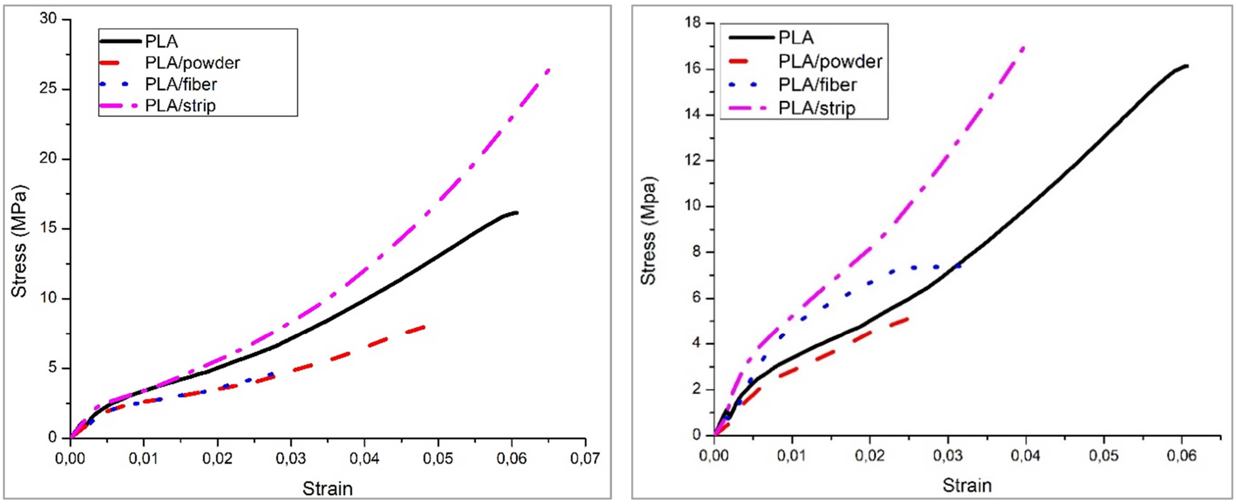
(a) (b) (c)

Figure 1. *(a) bamboo strip; (b) bamboo fiber; (c) bamboo powder.*

3. Results and Discussion

PLA/bamboo composites were successfully fabricated by hot press molding. There were traces of grease left on the sample surface. Grease was added to facilitate the separation between the final product and the mold. The high temperature of the hot press (220°C) melts the grease, which is eventually integrated with molten PLA. Thus, transparent grease should have been used for a better visual appearance of the sample. PLA pellets and bamboo were first mixed in solid condition before being heated and pressed. The tightly pressed condition does not allow stirring during the heating process. Thus, the distribution of powder or short fibers of bamboo was difficult to control.

The stress of composites was calculated as the load applied in Newtons per mm2 of rectangular surface area. While the strain is the ratio of length differences with the initial length of the sample test, Figure 2 (a) shows the strain-stress curve of composite PLA/bamboo in which the bamboo was pre-treated with water soaking. All curves follow the typical curve shape of composite materials, as the yield point is absent. PLA/bamboo strip has the highest tensile strength and ductility. However, the composite PLA/bamboo powder and PLA/bamboo fiber have lower values of tensile strength and ductility than pure PLA. It shows that the addition of powder or fiber from bamboo failed to improve the mechanical properties of composites. Figure 3 shows that the failure is due to shear stress in the middle part of the sample. It was found during visual observation of the sample product that the bamboo powder and fiber are not evenly distributed into the PLA matrix due to the difference in density. Bamboo has a lower density of 0.6–0.8 g/cm3 [8] than PLA with a density of 1.6–1.5 g/cm3. When the PLA was melted, bamboo short fiber or powder floated on the surface, causing uneven distribution. PLA/bamboo fiber gave the lowest value of strength as the failure was caused by the fiber being in transversal orientation or perpendicular to the load direction.



(a) (b)

Figure 2. The strain-stress curve for composite PLA/bamboo in which the bamboo was pre-treated with (a) water soaking and (b) 5% NaOH soaking.

Figure 2 (a) shows the strain-stress curve of composite PLA/bamboo in which the bamboo was pre-treated with 5% NaOH soaking. All the curves have similar characteristics to those found in water-soaked bamboo composites. Only the alkali-treated bamboo strip composite significantly improves the tensile strength of the composite. Both the addition of powder and the short fiber of bamboo result in lower values than pure PLA. However, with alkali treatment, PLA/alkali-treated fiber produced a higher value of tensile strength than PLA/water-treated fiber composites. The author assumes that alkali treatment works better on a limited surface area, as it was found in bamboo strips and fiber. On the contrary, PLA/water-treated powder has better results than PLA/alkali-treated powder.

A summary of the results of tensile testing can be found in Table 1.

The strain-stress curve for PLA/bamboo composite, in which bamboo was pre-treated with soaking in 5% NaOH, gave a similar response to tension loading. The absence of a yield point shows the plasticity characteristic and the absence of elasticity. Any deformation found during loading is permanent. The composite of PLA/bamboo powder and PLA/bamboo fiber also gave a lower value than pure PLA. However, the ductility of PLA/bamboo strips is lower than that of pure PLA. Soaking in water can dissolve the extractive compounds (lignin and hemicellulose), thus resulting in better adhesion between bamboo and the PLA matrix. Better interaction at the interface protects the bamboo cells from water molecules, thus providing better dimension stability [26].

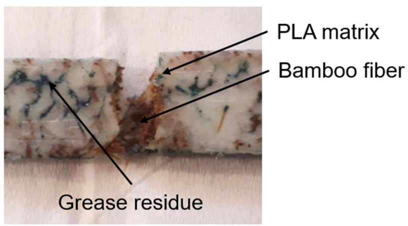


Figure 3. Fracture area.

Thus, water-soaked bamboo provides better mechanical tensile properties for composites than alkali-soaked bamboo.

The modulus of elasticity was then calculated as a ratio between stress and strain. Modulus elasticity reflects the rigidity or the material's ability to restrain the deformation. Alkali treatment with NaOH solution could also increase the crystallinity of bamboo fiber. Consequently, it increases the rigidity and decreases the ductility of composites. Table 1 shows that composites with alkali-treated powder or fiber as reinforcement agents have higher modulus elasticity but lower ductility. In other words, alkali increases the brittleness of bamboo as a composite reinforcement agent. However, long soaking durations can deteriorate the cellulose fiber, thus decreasing its tensile strength [27]. It should also be noted that PLA is not fully hydrophobic since it has a high carbonyl group content. For example, PLA is less hydrophobic than dimethyl ether. And for PLA, the degree of hydrophobicity depends on the parameters of the process, such as the solvent used during polymerization. It requires a special analysis tool to investigate the degree of PLA's hydrophobicity since the production parameters were not published. So, with those factors combined, the composite of PLA and NaOH-treated bamboo does not have good interface adhesion, resulting in a low tensile strength value.

Table 1. *Tensile properties of PLA/bamboo.*

	Tensile Strength (MPa)	Ductility (%)	Modulus of Elasticity (MPa)
PLA	16.72±0.75	6.07±0.095	237.59±16.8
Water-soaked bamboo			
PLA/bamboo powder	8.91±0.59	5.15±0.35	178.97±17.94
PLA/bamboo fiber	4.76±0.1	2.75±0.07	213.68±13.85
PLA/bamboo strip	27.91±0.66	7.9±0.01	580.69±67.42
Alkali-soaked bamboo (NaOH 5%)			
PLA/bamboo powder	5.14±0.18	2.5±0.015	379.36±10.29
PLA/bamboo fiber	7.36±0.14	3.15±0.035	334.19±17.13
PLA/bamboo strip	17.77±0.29	4.6±0.014	794.83±11.79

4. Conclusion

We have investigated the mechanical properties of a composite of PLA and bamboo treated with soaking in water or a solution of NaOH at 5%. All the composites were made by hot press molding with a bamboo composition of 10%. According to the values of tensile strength and modulus of elasticity, only bamboo strips can improve the mechanical properties of composites. The aqueous environment dissolved the amorphous hemicellulose and lignin, leaving the cellulose fiber. This process also modified the surface properties of bamboo so it could have better adhesion with the PLA matrix. However, a longer duration of 72 hours deteriorates the bamboo fiber and worsens the adhesion at the interface. Consequently, the tensile strength of alkali-soaked bamboo composites is lower than that of those soaked in water. Furthermore, alkali can increase the crystallinity, making the bamboo more brittle. As a polymer synthesized from renewable sources, PLA has distinct characteristics compared to other polyesters. With proper preparation techniques, PLA combined with natural fiber has great potential to be a renewable, green composite material.

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