Flexural Properties of PLA-Based Composites Reinforced with Strip, Short Fiber, or Powder of Bamboo

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Abstract. Food storage and food packaging materials belong to a group of food contact materials (FCM) that is highly regulated to ensure the health and safety of consumers. The choice of FCM is crucial because all types of FCM produce non-intentionally added substances (NIAS). The unknown substances are mixed together with the food and are consumed together. Therefore, bio-based and biodegradable materials are recommended since the excretion substances can be decomposed by human metabolism. One example is polylactide acid (PLA). PLA is made from potato or corn starch and comprises lactide acid monomers. However, the mechanical and thermal stability of PLA is relatively low. A four-year-old bamboo is incorporated into the PLA matrix to improve the mechanical stability of PLA. A freshly harvested bamboo is sun-dried for a week before it undergoes alkali treatment with NaOH 5%. After 72 hours of alkali soaking, the bamboo is rinsed and re-dried. The strip, short fiber, and powder of bamboo were obtained mechanically. The PLA/bamboo composites are made with 10% bamboo reinforcement by using a hot press molding machine. The flexural test was done to observe the bamboo shape's influence on the mechanical stability of composites. We found that each form of bamboo has a different surface contact with the PLA matrix. So, it significantly influences the bending strength of PLA/bamboo composites. In addition, the alkali treatment also influences the flexural properties as it modifies the interface adhesion between bamboo and PLA. The composites made of bamboo immersed in NaOH solution have a higher flexural modulus of elasticity indicating better rigidity.

Keywords: Alkali Treatment, Bamboo, Bending Properties, Composites, PLA

1 Introduction

Materials used for food storage is a part of food contact materials (FCM). Almost all FCM release a foreign substance unknowingly into the food. This migration is influenced by the fat content of the food and the porosity, thickness, and contact area of materials (Husain et al., 2015). The foreign substance could be an additive, monomer, oligomer, pigment, or other contaminant. Some are safe to consume if the

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amount is considerably low but some can be carcinogenic (Kato & Conte-Junior, 2021). Thus, to minimize the risk, bio-based and biodegradable materials are preferred.

Biodegradable materials are a group of materials that can be decomposed by living organisms. While bio-based materials are mostly natural polymers that are abundant in the environment. Generally, biodegradable materials are made of bio-based materials. However, not all bio-based materials can be decomposed naturally. One example of materials that belong to both groups is poly-lactide-acid (PLA) (Karimah et al., 2021). PLA is a polymer originating from corn starch. It has two optical isomers, L-PLA and D-PLA. The characteristic of PLA is highly dependent on the ratio between those two isomers. PLA is often used due to its low production energy and is economically beneficial. Even though the use of PLA can be challenging because of its low mechanical properties, high viscosity (Widantha et al., 2023), and high gas permeability (Hunter, 2003). Thus, incorporating a reinforcement substance is one solution to solve the problem.

Natural reinforcement is mandatory to maintain the general characteristics of biodegradable and bio-based materials. PLA-based composites reinforced with hemp, jute, pineapple, and bamboo fiber have been engineered to create environmentally safe materials (Tahir, 2013). Among them, bamboo is striking due to its abundant amount in tropical countries such as Indonesia, easy to cultivate, and better ductility than wood (Adrin et al., 2013). However, the mechanical properties of bamboo are varied with its diameter and culm thickness, showing the variation of fiber-bundle diameter (Naik et al., 2023).

Mechanical properties of composites are influenced by composition, distribution, size of reinforcement agent, and contact area with matrix. Several publications have reported the mechanical properties of PLA/bamboo composite with variations of bamboo shape: powder (Nukala et al., 2022), microfibrils (Puspita et al., 2019), and fiber bundle (Ochi, 2012). Those studies used tensile testing to quantify the mechanical properties. Previously, the variation of bamboo shape in the PLA matrix was evaluated by tensile testing (Baiti et al., 2023). Thus, in this research, the authors will evaluate the mechanical stability of PLA/bamboo composite by conducting flexural testing. The composites tested are reinforced with powder, fiber, or strips of bamboo with the same mass content. The influence of alkali treatment on the bamboo before composite making was also studied.

2 Methodology

A four-year-old *betung* bamboo (*Dendrocalmus asper*) was harvested from Klungkung Regency, Bali, Indonesia. We only used the segment located 2 meters high from the ground surface and has a 15 – 20 mm wall thickness. After being cut into thick strips, bamboo was sun-dried for a week since the water content can significantly improve the mechanical properties of bamboo (Wang et al., 2013). Then, bamboo was soaked in water and NaOH 5% (w/v) separately for 72 hours. The alkali treatment was done to dissolve the extractive substance. After rinsing in flowing water, the bamboo was sun-dried for 2 days and oven-dried for 2 hours at 60° C. The powder, fiber, and thin strips of bamboo were extracted mechanically. The PLA/bamboo composite was made through the hot press molding technique. We use the mold of ASTM D790 specimen. 10% of bamboo was incorporated into the PLA matrix for each specimen. Finally, the bending testing was done to evaluate the influence of bamboo's morphology and alkali treatment on the mechanical stability of the composites. The test is following the procedure explained in ASTM D790.

3 Result and Discussion

3.1 Result

The PLA/bamboo composites have been successfully made through the hot press molding technique. Each composite consists of 10% (w/w) bamboo. The bamboo powder was sieved to obtain a homogeneous size of 40 mesh. The bamboo fiber has a length of 10-15 mm.

Flexural testing is done using the universal testing machine with a maximum capacity of 5kN. The loading velocity was 1 mm/minute. The load and deflection were recorded during testing. The flexural strength was calculated by Equation (1).

$$\sigma_f = 3PL2bd2 \quad (1)$$

where:

σ_f = flexural stress (MPa)
P = load at a given point (N)
L = support span (mm)
b = width of beam tested (mm)
d = depth of beam tested (mm)

Meanwhile, the flexural strain is calculated by Equation (2).

$$\varepsilon f = 6DdL2 \quad (2)$$

where:

ε_f = flexural strain (mm/mm)
$\varepsilon f = 6DdL2$ = deflection of the center of the beam at a given point (mm)

Figure 1 shows the typical flexural strength and strain of composite reinforced with bamboo. Figure 1(a) compares the flexural strength and strain curve of composite whose bamboo was soaked in water. All of them have elastic response to the load even though only pure PLA and PLA/bamboo powder composite showed yield properties. Composite reinforced with bamboo strips gives the highest flexural strength, following by bamboo fiber and bamboo powder. However, bamboo fiber gives better maximum deflection. Failure started on the surface of the PLA matrix. When the contact between PLA and bamboo is broken, the composite is unable to withstand higher load. The addition of bamboo causes a decreasing in flexural strength due to the uneven distribution of bamboo and gas trapped in the hot press process. Despite that, we still can observe the influence of bamboo morphology on the flexural properties of PLA/bamboo composites.

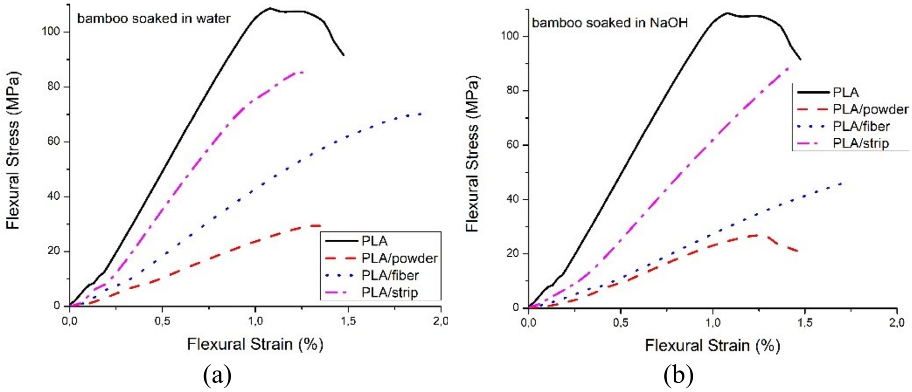

Figure 1. Typical flexural strength - strain curve of PLA/bamboo composite whose bamboo (a) is soaked in water and (b) is soaked in NaOH 5%

Meanwhile, Figure 1(b) compares the flexural strength and strain curve of composite whose bamboo was soaked in NaOH 5% (w/v). A similar pattern was found in the curve of composite reinforced with bamboo soaked in alkali. Only pure PLA and PLA/bamboo powder have the yield properties. PLA/bamboo strip has the highest flexural strength while PLA/bamboo fiber has the highest maximum deflection. It showed that surface treatment of bamboo modified the surface interaction between bamboo and PLA matrix. Bamboo powder has the highest contact area followed by fiber and strips. Thus, bamboo powder is more susceptible to surface modification.

3.2 Discussion

The flexural stress-strain diagram shown in Figura 1 is also used to calculate the flexural modulus of elasticity. It is the ratio of stress to strain, within the elastic region or it can be calculated by Equation (3).

$$E_f = L3P4d3wD \tag{3}$$

where:

E_f = flexural modulus of elasticity (MPa)

Generally, PLA has a hydrophobic surface. However, due to the carbonyl group, PLA still has a small portion of hydrophilic characteristics. Meanwhile, the bamboo surface is highly hydrophilic. Thus, incorporating bamboo into a hydrophobic matrix such as PLA requires surface treatment. The most common method is by doing alkali treatment or immersing the bamboo in NaOH solution. The alkali can dissolve extractive substances such as lignin and hemicellulose in bamboo (Das & Chakraborty, 2008). By doing so, the crystallinity of cellulose in bamboo is increased thus improving the adhesion between bamboo and polymeric matrix (Gandini & Belgacem, 2011; Wong et al., 2010). Better surface interaction can prevent water molecules from entering the composite structure and stabilize the physical and mechanical properties of PLA/bamboo composite (Febrianto et al., 2012). Figure 2(c) shows that for all types of composite, those using bamboo soaked in NaOH have higher flexural modulus signaling better adhesion between PLA and bamboo. However, alkali treatment should be done carefully because of the excessive concentration of NaOH and immersion duration can not only dissolve the extractive substances but also destroy the structure of cellulose. Since bamboo powder and fiber have a higher surface area, they are more sensitive to the alkali. Figure 2(a) shows that combining PLA with bamboo powder or fiber soaked in NaOH gives lower flexural stress. It implies that the cellulose structure in bamboo has been destroyed. Another report recommends doing alkali treatment with NaOH 4% (w/v) only for 30 minutes at 50 ºC which is faster than our 72 hours of immersion (Sugiman et al., 2019).

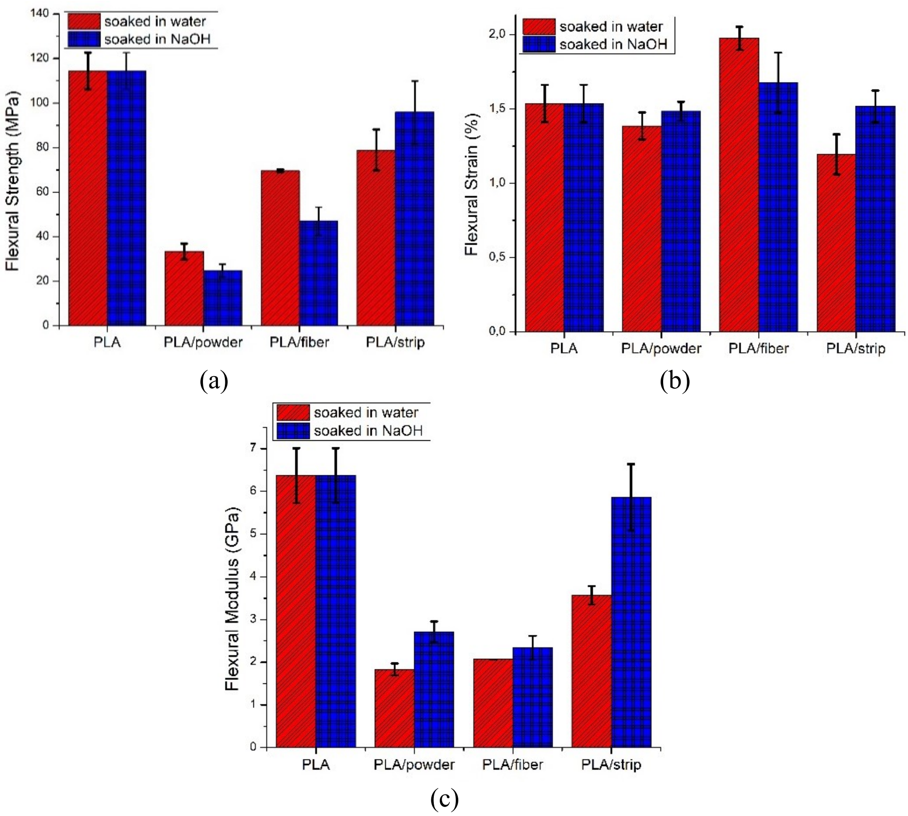

Figure 2. Comparison of (a) flexural strength, (b) flexural strain, and (c) flexural modulus of composites of PLA and bamboo soaked in water and NaOH 5%

4 Conclusion

We have investigated the influence of alkali treatment on bamboo and bamboo morphology on the flexural properties of PLA/bamboo composite. It is clear that the shape and distribution of bamboo significantly influence the flexural properties of composites. This is due to the difference in surface area. The mechanical stability highly depends on the adhesion between the bamboo surface and the polymeric matrix. The interface adhesion can be improved by alkali treatment. The composites using bamboo soaked in NaOH has a higher flexural modulus of elasticity. Despite all, the manufacturing of composites should be handled carefully to avoid porosity due to gas-trapped and uneven distribution of reinforcement agents.

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