EFFECTS OF FORMING PROCESSING CONDITIONS ON THE FLEXURAL PROPERTIES OF BAGASSE AND BAMBOO PLASTIC COMPOSITES

Shinichi Shibata *

The effects of processing conditions such as pressure, temperature, and holding time on the flexural properties of bagasse and bamboo biodegradable composites were investigated. Each sample of bagasse or bamboo was mixed with a corn-starch-based biodegradable resin and fabricated by a hot press forming method. The cross-sectional structure of the bagasse fiber was found to be porous and compressible, while that of bamboo was found to be more solid. The relationship between flexural strength, flexural modulus, and pressure in bagasse fiber was apparently different from that of bamboo due to the differences in the cross-sectional structure. In bagasse, the flexural strength and flexural modulus increased with the increase in pressure, whereas in bamboo those properties decreased. In bagasse, an increase in pressure made the fibers into a more compressed structure, increasing their flexural properties. In rigid bamboo, an increase in pressure caused the resin to extrude between fibers, and this resulted in lower flexural properties. At temperatures above 170 ^{o}C, the resin depolymerized thermally and the degree of polymerization decreased. Thus, the flexural modulus and strength decreased gradually with increase in holding temperature in both bagasse and bamboo composites. Furthermore, a maximum fiber volume fraction existed for both bagasse and bamboo plastic composites in the approximate range of 75% to 80%.

Keywords: Bagasse; Bamboo; Natural fiber; Composites; Processing conditions; Flexural modulus; Flexural strength

Contact information: Department of Mechanical Systems Engineering, University of the Ryukyus, Okinawa, 903-0213 Japan; E-mail: shibata@tec.u-ryukyu.ac.jp

INTRODUCTION

In recent years, studies on the utilization of lignocellulose materials as reinforcements in polymeric composites have increased due to the low density and biodegradability of these materials. The introduction of natural fibers into a polymer has been known to cause substantial changes in the resulting composites, particularly in the quality of mechanical properties and rigidity (Huda *et al.* 2005; Khalil *et al.* 2001; Chawla 1998; Luz *et al.* 2007; Cao *et al.* 2006; Das and Chakraborty 2009; Mohanty *et al.* 2005; Jimenez and Zaikov 2007).

Natural fiber composites such as flax, hemp, bagasse, jute, ramie, bamboo, coir, and sisal are emerging as a viable alternative to glass fiber composites, particularly in automotive, packaging, and building and are becoming one of the fastest growing additives for thermoplastics. Thus, natural fibers possess high potential for use as outstanding reinforcements in lightweight structures.

Natural fiber-reinforced bagasse and bamboo plastic composites have gained more attention because of their low cost, processing advantages, good strength, and

stiffness. The parameters affecting the properties of the fiber-reinforced composites are fiber content, fiber-resin adhesion, fiber length, fiber aspect ratio, fiber dispersion, and orientation (Fukuda and Chou 1982; Mathew and Joseph 2006; Sanomura and Kawamura 2004). The world's natural resources are decreasing, and the demand for sustainable and renewable raw materials continues to rise. These natural fibers obtained from renewable sources have less impact on the environment than do petroleum-based materials.

Many researchers have studied the mechanical properties of natural fiber composites. Jain *et al.* (1992) evaluated the tensile, flexural, and impact strengths of bamboo and bamboo fiber-reinforced plastic composites. Goda and Cao (2007) performed research and development on fully green composites reinforced with natural fibers. Sgriccia *et al.* (2008) examined the characterization of natural fiber surfaces and natural fiber reinforced composites as a replacement for glass fiber composites. Takagi and Ichihara (2004) examined both the tensile and flexural strengths of bamboo fiber-reinforced "green" composites, and found that they were strongly affected by fiber aspect ratio and fiber content. Takagi and Asano (2008) also evaluated the effects of processing conditions on the flexural properties of cellulose nano-fiber-reinforced "green" composites and demonstrated that flexural strength and flexural modulus increased with the increase in molding pressure, and that they were affected by preparation methods and conditions. Shibata *et al.* (2005) have investigated the effects of the volume fraction and the lengths of natural fibers on the flexural properties of biodegradable composites. Kenaf and bagasse were mixed with corn-starch biodegradable resin, and composite flexural specimens were fabricated by press forming. The flexural modulus of the natural fiber composite made from kenaf and bagasse increased, with an increase in fiber volume fraction to 60% for kenaf and to 66% for bagasse.

Few researchers have studied the effects of processing conditions on the flexural properties of bagasse and bamboo biodegradable plastic composites. This study examined the relationship between processing pressure, temperature, holding time, and the flexural properties of bagasse and bamboo plastic composites.

EXPERIMENTAL

Materials

The bamboo, which was 0.19 mm in diameter and 300 to 500 mm long, was supplied by Toyota Boshoku Co. Ltd., Japan. Before the forming, the bamboo fibers were cut into 10 mm long pieces. The bagasse fibers were collected after being crushed for juice extraction with a crushing machine. The long bagasse fibers were shortened to an average length of 10 mm. The diameter of each was 0.35 mm. The bagasse fibers were cleaned in hot water at 80 ºC for one hour. This procedure removed the fine bagasse particles, sugar residues, and organic materials from the samples. Then both the bamboo and bagasse fibers were dried at 60 ºC for 24 hours.

The physical and mechanical properties of the bagasse and the bamboo used as fibers are shown in Table 1. The emulsion-type corn starch-based biodegradable resin, CP-300, was supplied by Miyoshi Oil & Fat Co. Ltd., Japan (Glass transition temperature (T_g): -60 ºC, softening temperature 55 to 62 ºC). The resin was dried and chopped into uniform pellets with 1 to 2 mm diameters. The physical properties of this biodegradable resin are shown in Table 2.

Table 1. Properties of the Bamboo and the Bagasse used as Fibers

	Young's modulus (MPa)	Tensile strength (MPa)	Specific gravity (kg/m^3)	Diameter (mm)
Bamboo	18500	450	1030	0.19
Bagasse	4500	107	360	0.35

Table 2. Properties of the Biodegradable Resin used as Matrix

Density (g/cm^3)	1.18
Water Absorption (%)	2.0
Tensile strength (MPa)	12.20
Tensile elongation (%)	550
Young's Modulus (MPa)	431
Flexural strength (MPa)	13.3
Flexural modulus (MPa)	460
Specific gravity (kg/m^3)	1160

Press Forming

The natural fiber composite specimen was fabricated by a hot press forming method. Figure 1 shows the fabrication process of the composites. At first, the cylinder and the piston were heated to the desired temperature for 15 minutes in order to achieve homogeneous heat transfer in the mold. After that, the mold opened, and immediately half amount of the fibers were put into the metal cylinder. Then, both the resin and fibers, which had not yet been mixed, were placed into the cylinder. The orientation of the fibers was random and two-dimensional. Also, the fibers were randomly dispersed and no resin-rich area was observed in the plastic composites. Note that there was a tiny gap between the piston and the cylinder to allow the escape of air. For this reason, only the resin could leak out of the clearance when compressive pressure was applied on the piston. Moreover, the amount of the leaked resin varied depending on molding pressure; this affects the fiber volume fraction of the final composites. The specimen that was obtained was circular in shape (30 mm in diameter and 1.5 to 2.0 mm in thickness), and is shown in Fig. 2.

Authors have reported that bagasse can be compressive, and that the compression contributes to the flexural strength and the flexural modulus. In this study, the compression ratio *K*, that is, the ratio of the compressed volume to the non-compressed volume, was defined as,

$$K = V_f' \ / \ \left[V - \left(\frac{W - W_f}{\rho_m} \right) \right] \quad (1)$$

where V'_f, V, W, W_f, and ρ_m denote original non-compressed fiber volume, volume of the composite, weight of the composite, weight of the fiber, and density of the matrix, respectively.

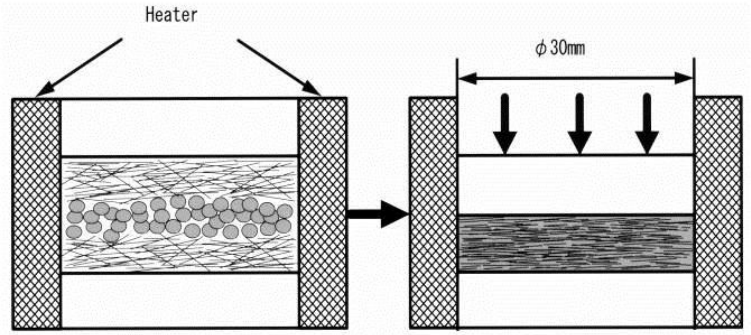

Fig. 1. Hot press forming with the cylindrical mold: (left) before molding, (right) after molding

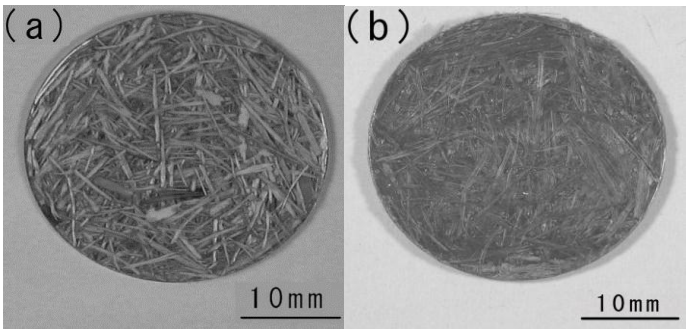

Fig. 2. Appearances of (a) bagasse and (b) bamboo plastic composites after hot press forming

Methods

Flexural test

A flexural test was carried out at each condition with five specimens using the universal testing machine (Orientec Co. Ltd. STA-1225, Japan) in accordance with ISO 178 specifications. Both the flexural strength and the flexural modulus were determined by averaging the values of five specimens generated from the three-point bending test. The test used a span length of 22 mm and a cross-head speed of 1 mm/min. The specimens used in the flexural test were 30 mm in length, 15 mm in width, and 1.5 to 1.7 mm in thickness. The flexural modulus was determined by the initial derivative line of the load-displacement curve. The derivative part was defined as being between 0 and 15% of the maximum load. The flexural strength was calculated using the maximum load.

RESULTS AND DISCUSSION

Effect of Pressure on the Flexural Properties of Bagasse and Bamboo Plastic Composites

Figures 3 (a) and (b) show the cross sectional structures of bagasse and bamboo fibers. Bagasse fibers were found to be porous in structure, while those of bamboo were more solid. Figures 4 (a) and (b) show the effects of pressure on the flexural modulus and on the flexural strength in bagasse and bamboo plastic composites. All of the composites were fabricated at 160 ºC and for a 10 min holding time. The applied pressure was adjusted to different values.

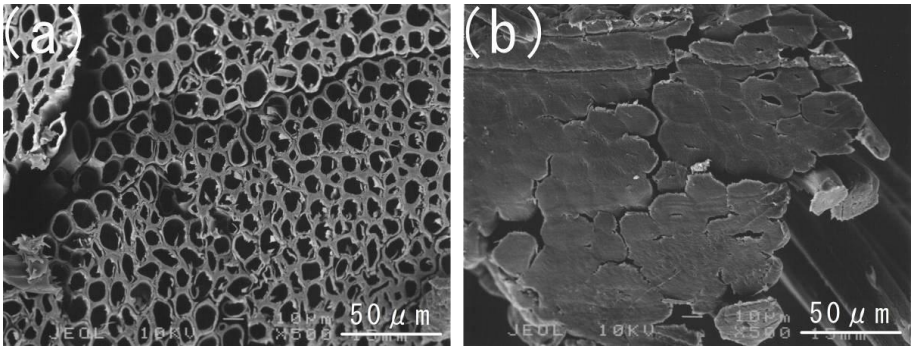

Fig. 3. Cross sectional structures of (a) bagasse and (b) bamboo fibers

In bagasse, both the flexural modulus and the flexural strength increased with the increase in pressure, whereas in bamboo, the flexural modulus and flexural strength decreased with the increase in pressure, except at 4.9 MPa. Thus, opposite results were obtained for the bagasse and bamboo plastic composites.

Figures 4 (c) and (d) show the relationship between fiber volume fraction, compression ratio, and pressure in bagasse and bamboo plastic composites, respectively. In bagasse, both the fiber volume fraction and the compression ratio increased with the increase in pressure, whereas in bamboo only the fiber volume fraction increased to 88 %. The increase in the fiber volume fraction was due to the leak of resin from the clearance of the piston and the cylinder when the pressure was applied, as described in the experimental method.

The maximum compression ratios in bagasse and bamboo were 430% and 150%, respectively. These experimental results concurred with the microstructure observation that is shown in Fig. 3.

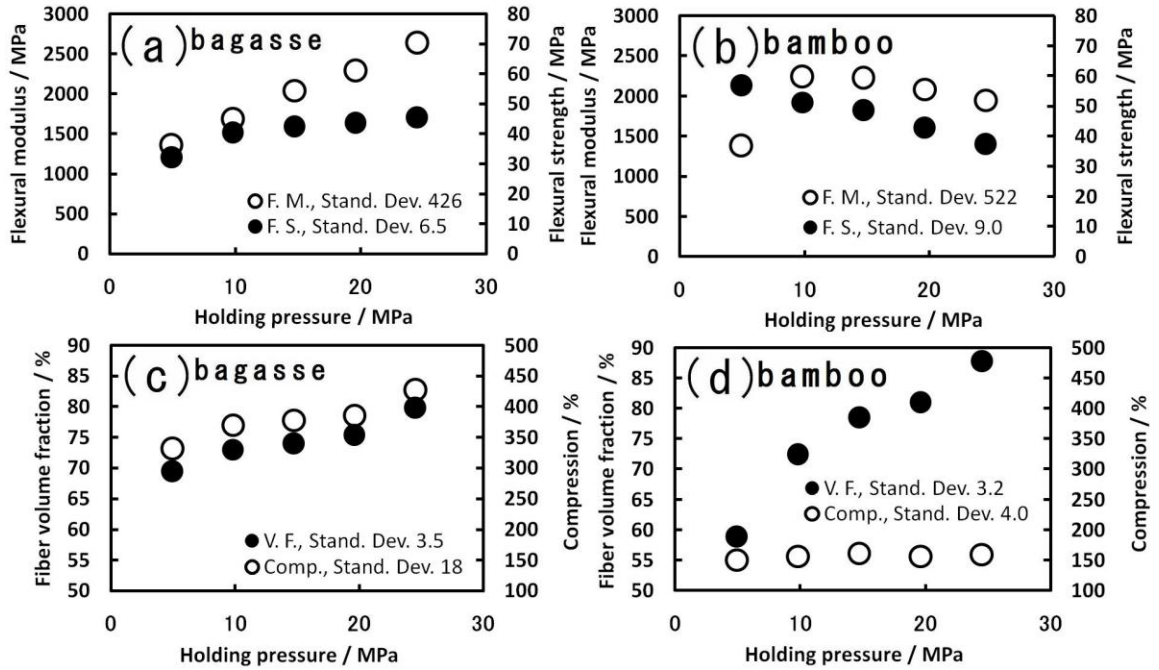

Fig. 4. The relationship between flexural properties and processing pressure in (a) bagasse and (b) bamboo. The relationship between fiber volume fraction and the compression ratio of fibers in (c) bagasse and (d) bamboo.

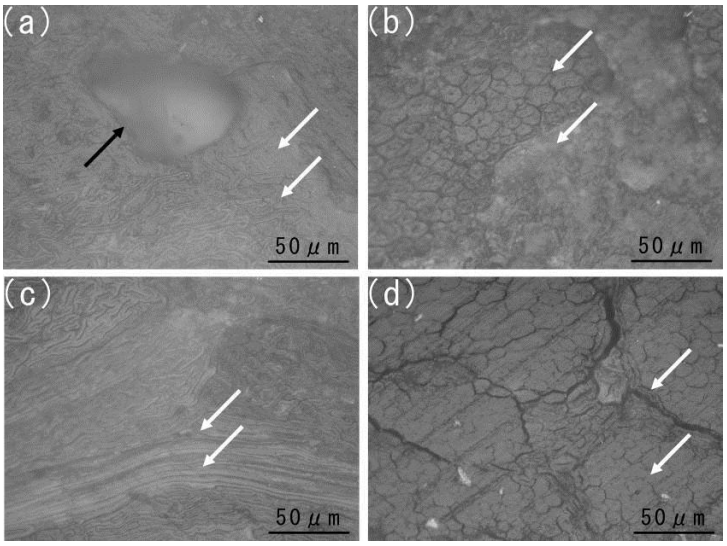

Fig. 5. Optical microphotographs of the cross section of the composite specimens (a) bagasse at 4.9 MPa, (b) bamboo at 4.9 MPa, (c) bagasse at 19.6 MPa, and (d) bamboo at 19.6 MPa.

The higher pressure led to more resin leaking and resulted in a higher fiber volume fraction. Furthermore, in bagasse, the higher pressure led to a higher compression ratio, which contributed to the flexural strength and flexural modulus. Thus, it was established that the flexural properties increased with the increase in pressure.

However, in the case of bamboo, the opposite results were obtained. To clarify the reason for this, an observation of the microstructure of the composite was conducted using an optical microscope.

Figures 5 (a) and (b) show the microstructures of bagasse and bamboo at 4.9 MPa, while Figs. 5 (c) and (d) show the microstructures at 19.6 MPa. The arrows in the images indicate either fiber or resin. In Fig. 5 (a) a cavity is indicated by the black arrow in the picture, and there was much resin area at a pressure of 4.9 MPa. On the other hand, the bagasse fibers were apparently compressed at a pressure of 19.6 MPa, as shown in Fig. 5 (c). In the case of the bamboo, no compression of the fibers was found as it was for bagasse. However, many cracks between the fibers were found, as indicated by the arrow in Fig. 5 (d). There was apparently less matrix resin in the vicinity of the crack. The reason for this is not clear at this point. The matrix resin could leak more easily between the near-solid bamboo fibers than between the flexible and compressive bagasse fibers. Thus, it could be concluded that these cracks in the bamboo composites increased with the increase in pressure and led to a decrease in the flexural strength and the flexural modulus, as shown in Fig. 4 (b). In the range from 4.9 MPa to 9.8 MPa, the increase in the flexural properties of the bamboo was considered to be due to an increase of fiber volume fraction from 57% to 73%, a dramatic increase, with sufficient resin between fibers in the composites.

Effect of Temperature and Holding Time on the Flexural Properties of Bagasse and Bamboo Plastic Composites

Figures 6 (a) and (b) show the effect of temperature on flexural strength and flexural modulus in bagasse and bamboo plastic composites. The processing conditions

were press pressure 14.7 MPa and holding time 10 min, and only the processing temperature was changed, from 130 ºC to 210 ºC.

As shown in the figures, the maximum values and the flexural strength and flexural modulus were clearly observed at 170 ºC in both bagasse and bamboo.

Figures 6 (c) and (d) show the relationship between fiber volume fraction, compression ratio, and temperature. In both bagasse and bamboo, the compression ratios were consistent despite the increase in processing temperature from 130 ºC to 210 ºC. The compression ratios in bagasse and bamboo were approximately 350% and 150%, respectively. However, the behavior of the fiber volume fraction in bagasse was different from that in bamboo. In bagasse, the volume fraction was constant until 170 ºC and then increased clearly after reaching 170 ºC, whereas in bamboo, the volume fraction increased after reaching 130 ºC. This experimental result indicated that at relatively lower temperatures, from 130 ºC to 170 ºC, the resin may tend to be not extruded but more easily held between fibers at the same pressure in the case of the flexible bagasse fiber rather than that of the rigid bamboo fiber. This experimental result concurred with our projection of the reason why, in bamboo, the resin was extruded at higher pressures, as in Fig. 5 (d).

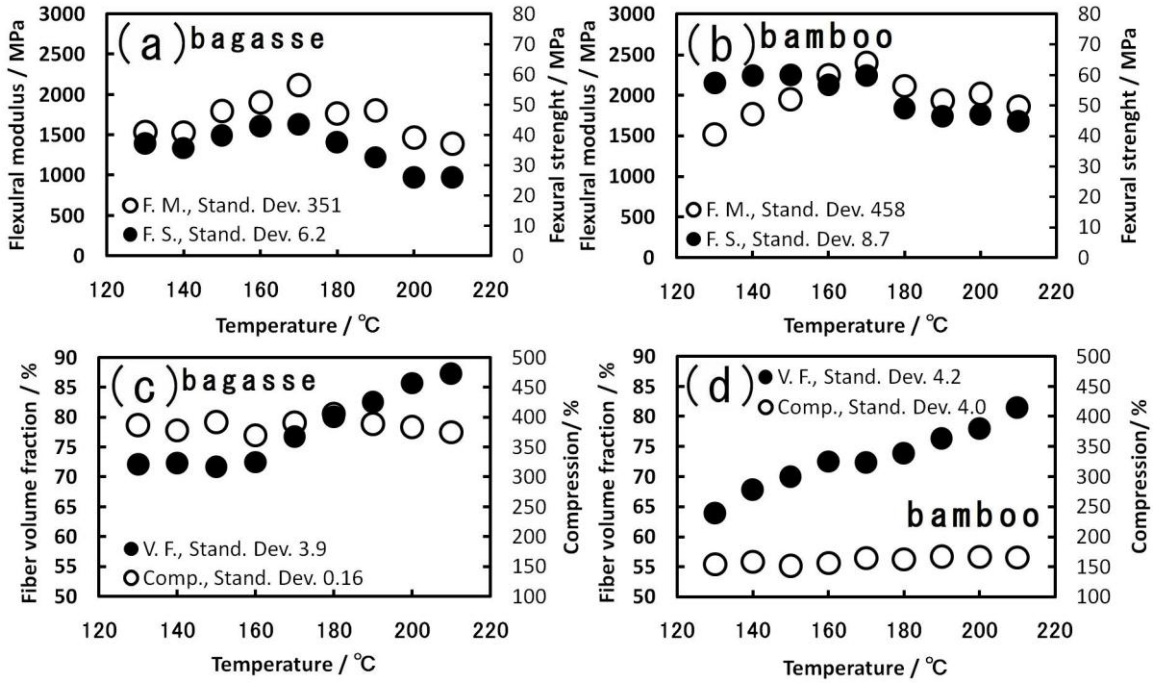

Fig. 6. The relationship between flexural properties and processing temperature in bagasse (a) and bamboo (b). The relationship between fiber volume fraction and the compression ratio of fibers in bagasse (c) and bamboo (d).

Furthermore, above 170 ºC, the color of the resin changed from the original milk white to yellow, and the resin became brittle in appearance. Thus, the decrease in flexural properties above 170 ºC was thought to be due to the depolymerization of the matrix resin. Figures 7 (a) and (c) show the microstructures of the bagasse composites at (a) 130 ºC and (c) 200 ºC. The ratio of resin to bagasse fiber apparently decreased at 200 ºC, and some cracks were found.

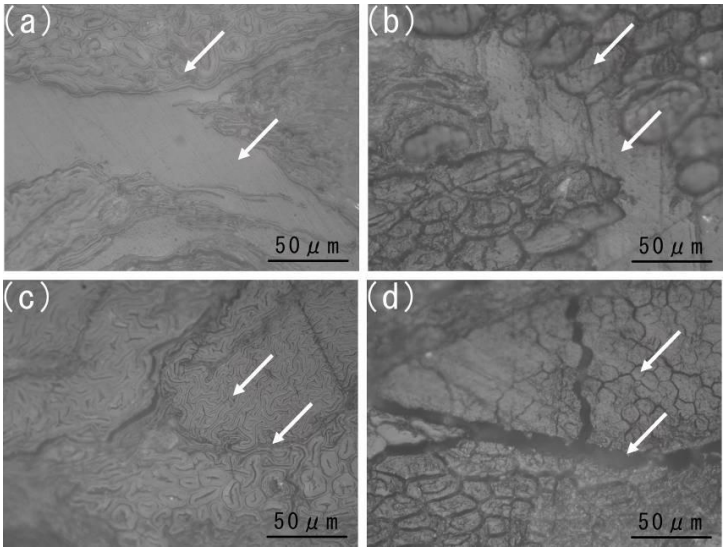

Fig. 7. Optical microphotographs of the cross section of the composite specimens: (a) bagasse at 130 ºC, (b) bamboo at 130 ºC, (c) bagasse at 200 ºC, and (d) bamboo at 200 ºC

Figures 7 (b) and (d) show the bamboo composites at (b) 130 ºC and (d) 200 ºC. At 200 ºC, many cracks between fibers were found. Thus, the cracks occurred due to the embrittlement by thermal depolymerization of the resin, even though fiber ratio increased as a result; this fact is considered as a cause of the decrease in flexural properties above 170 ºC.

Figures 8 (a) and (b) show the relationship between the flexural modulus, strength and holding time. The processing conditions were press pressure 14.7 MPa and temperature 160 ºC. The holding time was changed from 1 to 30 min.

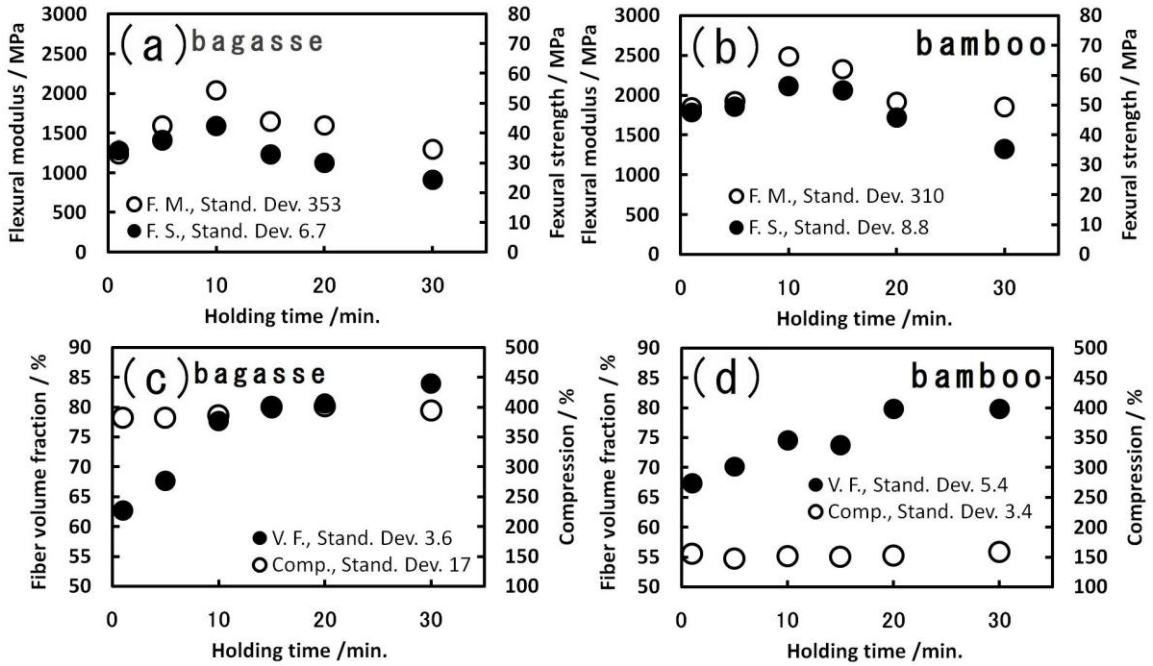

Fig. 8. The relationship between flexural properties and the holding time in (a) bagasse and (b) bamboo. The relationship between fiber volume fraction and the compression ratio of fibers in (c) bagasse and (d) bamboo.

As shown in both bagasse and bamboo plastic composites, the flexural properties showed a maximum at 10 min and then decreased.

Figures 8 (c) and (d) show the relationship between fiber volume fraction, compression ratio, and holding time. The volume fraction increased steeply from 1 to 10 min and then gradually increased beyond 10 min. The fiber compression was consistent – 350% in bagasse and 150% in bamboo. Thus, the fiber volume fraction increased, whereas all flexural properties in both fibers decreased. With longer holding times, especially those more than 10 min, the color of the resin changed as described. Thus, it is suggested that the longer holding time might have caused the increased depolymerization of the resin and the decrease in the flexural properties. In both fibers, the increase between 1 min to 10 min is due to the increase in the fiber volume fraction. At shorter holding times, the optimum fiber volume fraction might not be achieved. Thus, there should be an optimum holding time in order to produce the highest-performing natural fiber-reinforced composites.

CONCLUSIONS

1. In bagasse, the flexural modulus and strength increased with the increase in pressure. This was due to the increase in fiber volume fraction and in compression ratio of the fibers. However, in bamboo, the flexural strength and flexural modulus decreased with the increase in pressure. At higher pressure, bamboo, which is not compressive and is less flexible, extruded matrix resin from the composites, which resulted in an insufficient amount of resin between fibers at high pressure. The optimum fiber volume fractions, which indicated the maximum flexural values, were found to be in the range of 75% to 80% for both bagasse and bamboo plastic composites.
2. In both bagasse and bamboo, the flexural properties showed maximum values at 170 ºC in the case of the corn starch-based biodegradable resin. At temperatures below 170 ºC, the fiber volume fraction was relatively low, whereas at temperatures above 170 ºC, the resin underwent depolymerization and became brittle.
3. It was revealed that there is an optimum holding time for the maximum flexural properties in both bagasse and bamboo plastic composites. With shorter holding times, the fiber volume fraction was found to be below optimum. With longer holding times, the resin gradually depolymerized and became brittle. This occurred for both bagasse and bamboo plastic composites.

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Article submitted: July 19, 2012; Peer review completed: August 17, 2012; Revised version received: August 27, 2012; Accepted: September 3, 2012; Published: September 17, 2012.