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ORIGINAL ARTICLE

Mechanical properties of bamboo fiber bundle-reinforced bamboo powder composite materials

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Abstract

This paper reports the mechanical properties of bamboo fiber bundle-reinforced bamboo powder composite materials. Bamboo fiber bundle-reinforced bamboo powder composite materials were made from bamboo powder as matrix and bamboo fiber bundles as reinforcement arranged in random directions. The tensile and flexural strengths of the fabricated products were investigated. First, the effect of the water content of bamboo powder and molding temperature on the strength characteristics was studied. The results showed that the bamboo powder product prepared with a water content of 7.2% and molded at a temperature of 200 °C exhibited the highest adhesive strength between short fibers and bamboo powder. The tensile and flexural strengths of the bamboo fiber bundle-reinforced bamboo powder composite materials increased at temperatures ranging from 160 to 180 °C but decreased at 200 °C. The strengths of the composite materials fabricated at 200 °C were reduced because of the decrease in the strength of the fiber bundle itself. Therefore, 180 °C was concluded to be the most suitable molding temperature in terms of fiber bundle reinforcement. The bamboo fiber-reinforced bamboo powder composites molded at 180 °C and with a fiber bundle content of 70% exhibited the highest tensile and flexural strengths, at 45.0 and 101.4 MPa, respectively, with a density of 1.42 g/cm^3. These results are equivalent to those of engineering plastics such as PVC and POM, indicating that the prepared composite materials are suitable substitutes for plastics in terms of density, tensile and flexural strength.

1 Introduction

In recent years, the life cycle of everyday household goods, industrial products, and other similar manufactured goods has declined, and the problem of waste management has been aggravated (Letcher 2020). In particular, plastic products are indispensable as they are used extensively in diverse areas such as electric products, office supplies, sports goods, and automobile parts. Nevertheless, a significant amount of these products is disposed of in sanitary landfills after use and sometimes may even be exhausted because plastics are made of petroleum. Hence, it is important to develop an alternative to petroleum-based plastic products. Fiber-reinforced plastics (FRPs), including carbon and glass fiber-reinforced polymers, have several advantages such as light weight, superior strength, and high erosion resistance and are used in an extensive range of manufactured goods. However, FRPs have an adverse effect on the global environment (Vo Dong et al. 2015); they are fossil fuel-based, non-biodegradable, and emit harmful gases such as hydrogen and dioxins when incinerated. Clearly, the usage and disposal of conventional FRPs are a hindrance to the global objectives of zero emissions and recycling, and importance needs to be ascribed to the degradation of FRPs once they have been eliminated. The utilization of biodegradable resin (Letcher 2020; Tian and Bilal 2020), instead of conventional plastics not decomposing naturally, may serve as the most effective measure against such waste problems. When biodegradable resin is buried in the ground, it is decomposed by the action of microbes and is finally converted to water and carbon dioxide, which are absorbed by plants. However, biodegradable resin has a poor strength and is costlier than conventional resin. The application of natural plant fibers in FRPs to replace carbon and glass fibers is receiving attention because of advantages such as easy waste disposal, renewability, low cost, and biodegradability. Recent studies have been conducted to examine the development of biodegradable composite materials made using natural plant fibers, such as kenaf (Kudori et al. 2019; Yorseng et al.

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2020), sisal (Yorseng et al. 2020), flax (Musa et al. 2020), hemp (Neves et al. 2020), jute (Saravanana and Gnanavel 2020; Naik et al. 2019), banana (Saravanana and Gnanavel 2020; Rana et al. 2020), and ramie (Han et al. 2020; Chen et al. 2010), as a reinforcement for biodegradable resin. Moreover, replacing Kevlar (Jawaid and Siengchin 2019) fabric with an eco-friendly light-weight material, together with improved mechanical, ballistic, and thermal properties, has become an interesting research approach to achieve superior properties of hybrid composites. Currently (Rangappa et al. 2020), "eco-friendly" and "sustainability" have become important criteria to develop household or industrial products. Research and development efforts have been essentially directed towards using more ecofriendly and sustainable materials instead of using fossil-based non-biodegradable and non-renewable materials. Green composites are widely used in various applications such as automotive, aerospace, construction and building materials, household products, electronic and biomedical applications, packaging industries, etc. Vinod et al. (2020, 2021) reported on the surface treatment of bio-based composite materials and their fibers. The current global scenario has a great impact on the development of new bio-based materials due to its vital advantages that are helpful in replacing synthetic and hazardous materials. Researchers, scientists, and academicians are more focused on environmental conservation by developing sustainable bio-materials to preserve the earth. The development and property enhancement of novel Muntingia calabura bark micro-fiber reinforced bio-epoxy composite was achieved through surface modification techniques using NaOH and silane. Finally, based on improved results, this novel plant fiber was identified as a potential resource of environment friendly and sustainable raw material as reinforcement in polymer composites, which can be used to develop green composites for lightweight structural applications.

In the past, bamboo was part of the daily life of Japanese people. For several decades, the demand for bamboo has decreased because of the import of low-priced bamboo shoots from China and the emergence of plastic materials. Moreover, bamboo grows faster than forest wood. To address the issue of plastic waste and effectively utilize barren bamboo groves, this study was aimed to investigate whether bamboo can effectively be used as a substitute for plastic, which is currently used in many fields.

The purpose of this work was to manufacture press-molded bamboo powder and bamboo fiber bundles to further improve their strength. The applications of this material are single-cycle products such as personal computers, printers, and copiers. First, specimens were fabricated by hot-pressing bamboo powder. The effects of water content and molding temperature on the mechanical properties were investigated. A high-strength bamboo material was fabricated using bamboo powder reinforced by bamboo fiber bundles and arranged in random directions. The bamboo fiber-reinforced bamboo powder composite materials were molded from fine bamboo powder and bamboo fiber bundles with a length of 10 mm. The density, tensile strength, and flexural strength of the resultant materials were investigated, which were subsequently compared with those of general plastic materials and engineering plastics.

2 Materials and methods

2.1 Sample materials

In this study, bamboo (*Phyllostachys heterocycla f. pubescens*) was used as raw material, and, bamboo powder and bamboo fiber were used as the matrix and reinforcement, respectively. Bamboo is an isotropic composite material having short fibers randomly arranged. Bamboo powder extracted by machining was used. A bamboo tree was felled, and bamboo powder was obtained using bamboo powder manufacturing equipment. Figure 1a shows the

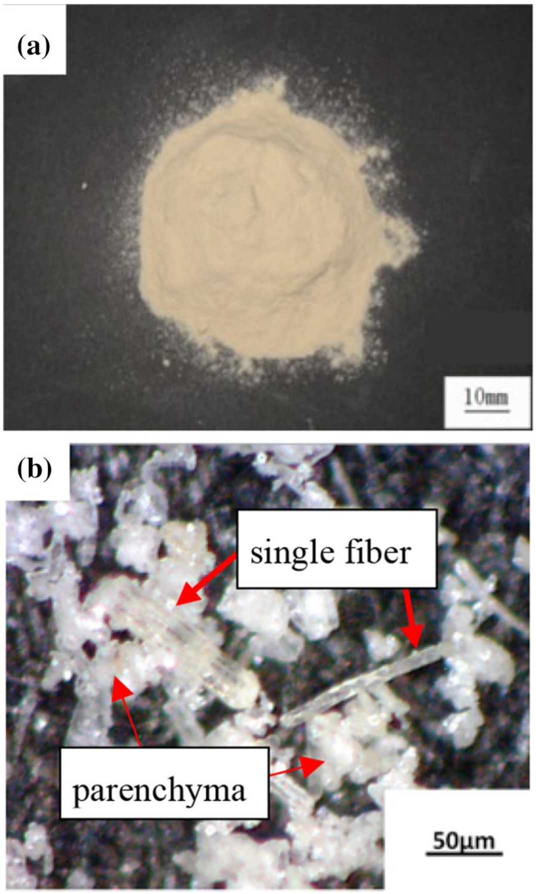

Fig. 1 Images of the bamboo powder. **a** general view **b** magnified view

image of the bamboo powder, and Fig. 1b shows its magnified view. From Fig. 1a, it can be seen that the bamboo powder appears uniform and fine; however, single fibers (100–300 µm in length and 5–15 µm in diameter) and infinitesimal parenchyma cells (20–100 µm) can be seen in the magnified image (Fig. 1b). The principal components are cellulose (60%), hemicelluloses (10–20%), and lignin (20–30%) (Jain et al. 1992). The steam explosion method (Ochi 2002) was applied to obtain the bamboo fiber bundles. In this method, when bamboo-containing water is heated for 40 min at a temperature of 180 °C and a pressure of 980 kPa by using the container, the bamboo is quickly released into the atmosphere. The liquid water evaporates into steam, thus destroying the parenchyma cells inside the bamboo. Figure 2 shows the image of the bamboo fiber bundles (Fig. 2a) and a magnified view (Fig. 2b). The length and diameter of the bamboo fiber bundles were 10 mm and 100–200 µm, respectively. The bamboo fiber bundles were cut to a length of 10 mm using a pair of scissors.

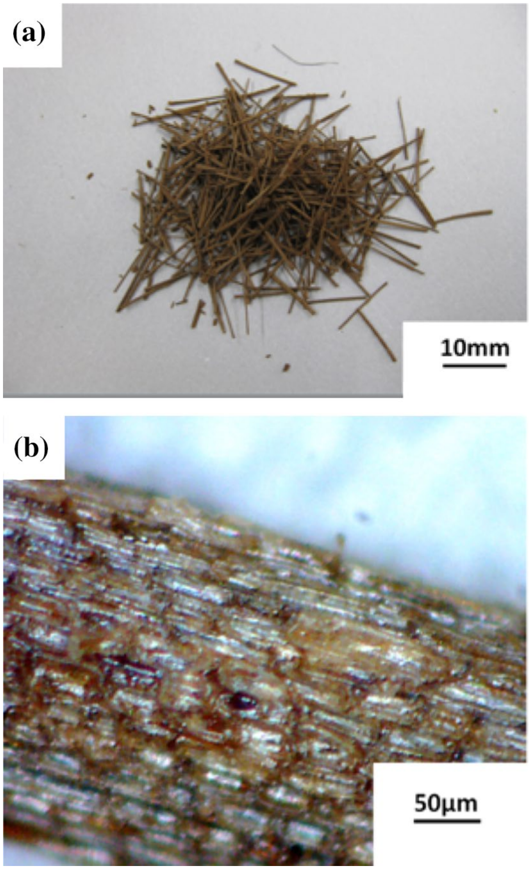

Fig. 2 Images of the bamboo fiber bundle **a** general view **b** magnified view

2.2 Preparation of specimens with different water contents

The bamboo powder was exposed to three humidity conditions (0, 50, and 90%). The 0% condition was selected because it represents a state without water. A 90% value was chosen instead of 100% as it represents the maximum value of the experimental device. The 50% humidity condition represents the median of the 0 and 100% conditions. Bamboo powder specimens with three different water contents were prepared using an oven [ETTAS, EO-300B] and a thermo-hygrostat chamber [ISUZU, YP-2001]. The 0% humidity condition was realized using an oven, and 50% and 90% humidity conditions were achieved using the thermo-hygrostat chamber. Next, the water content was calculated based on the difference in mass before and after the bamboo powder was dried; it was also measured at intervals of 30 min using a moisture meter (AND, MB45).

2.3 Fabrication of specimens using bamboo powder

The specimens for the strength test were prepared using a metallic mold and hot-press machine (AS ONE, HC 300-15). First, to investigate the effects of water content inside the bamboo powder on the mechanical properties, three types of specimens with different water contents (0, 50, and 90%) were molded. Table 1 lists the molding conditions and water contents of the bamboo powder. To examine the effects of molding temperature on the mechanical properties, three types of specimens were molded at different molding temperatures (160, 180, and 200 °C). These temperatures were selected because the strength of the natural fibers decreased at 160–200 °C. Table 2 lists the molding conditions of the bamboo powder. To prepare the specimens conforming to the conditions listed in Table 2, bamboo powder was placed in a metallic mold and heated to the set temperature in the range of 160–200 °C. The

Table 1 Molding conditions (effect of water content)

Molding temperature (°C)	Humidity (%)
200	0
	50
	90

Table 2 Molding conditions (effect of molding temperature)

Molding temperature (°C)	Humidity (%)
160	50
180	
200	

specimens were hot-pressed at 65 MPa. Dumbbell-type tensile specimens were produced with a parallel portion length of 60 mm, gripping length of 20 mm, total length of 175 mm, width of 10 mm, and thickness of 3 mm. The flexural test specimens had a width of 15 mm, length of 100 mm, and thickness of 3 mm. After molding the test specimen, it was stored in a desiccator at a humidity of 50 ± 5%.

2.4 Fabrication of bamboo fiber-reinforced bamboo powder composite specimens

Table 3 lists the molding conditions and fiber bundle content. The fiber bundle contents were 30, 50, and 70%. The molding temperatures were 160, 180, and 200 °C, and the humidity was 50%. Bamboo fiber-reinforced bamboo powder composite materials were produced using a metallic mold and a hot-press machine (AS ONE, HC 300-15). To mechanically test the specimens prepared under the conditions listed in Table 3, the bamboo fiber bundle and powder were placed in a metallic mold, held at the three selected molding temperatures, and pressed at 65 MPa. The dimensions and shapes of the test pieces were the same as those described in Sect. 2.3. Figure 3 shows the diagram of the composite material preparation.

Table 3 Molding conditions and fiber bundle content (effects of molding temperature and fiber content)

Molding temperature (°C)	Humidity (%)	Bamboo powder (%)	Bamboo fiber (%)
160	50	50	50
180		70	30
		50	50
		30	70
200		50	50

2.5 Mechanical testing

Tensile and three-point flexural tests were performed using a mechanical testing machine (SHIMADZU Autograph, AG-250kNE), in accordance with JIS K7161 (plastics determination of tensile properties) and JIS K7171 (plastics determination of flexural properties), respectively. The tensile test was conducted at a gauge length of 50 mm and a strain rate of 1 mm/min according to JIS K7161. The strain was measured using an extensometer (SHIMADZU AXTENSOMETER type ST-50-10-25). Three-point flexural strength tests were carried out at a span length of 48 mm and a crosshead speed of 1 mm/min according to JIS K7171. Five test specimens were molded and analyzed under each condition. To account for the variation in data, average values were calculated, and a statistical analysis was conducted based on a 95% confidence interval.

3 Results and discussion

3.1 Effects of water content on mechanical properties of bamboo powder product

3.1.1 Water content of bamboo powder

Figure 4 shows the relationship between the water content and processing time when bamboo powder was treated under humidity conditions of 0, 50, and 90%. The water content of the bamboo powder treated at 50% and 90% humidity remained constant at approximately 180 min; the water contents in these cases were 7.2% and 13.4%, respectively. The water content of the bamboo powder treated at 0% humidity remained constant (0.4%) at approximately 60 min. Figure 5 shows a proportional relationship between humidity and water content.

Hereinafter, bamboo powders exposed to humidity conditions of 0, 50, and 90% are denoted by 0.4, 7.2, and 13.4%, respectively.

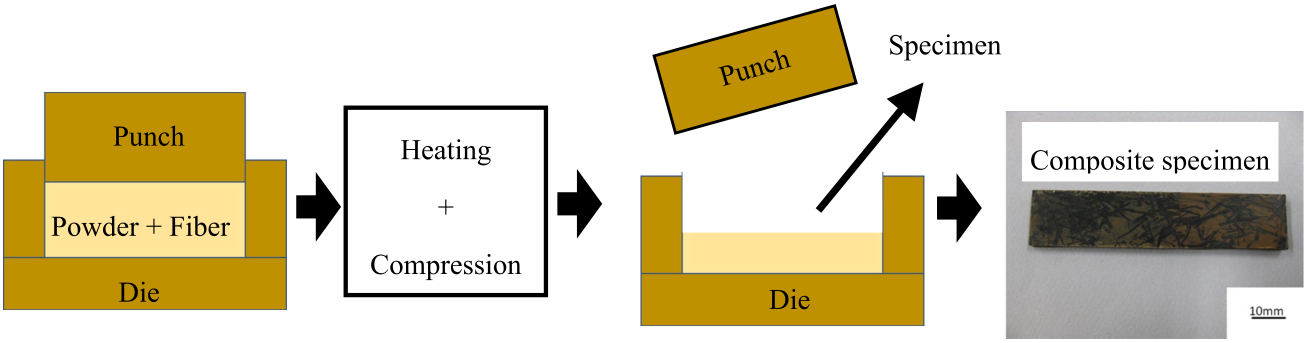

Fig. 3 Diagram showing the composite preparation process

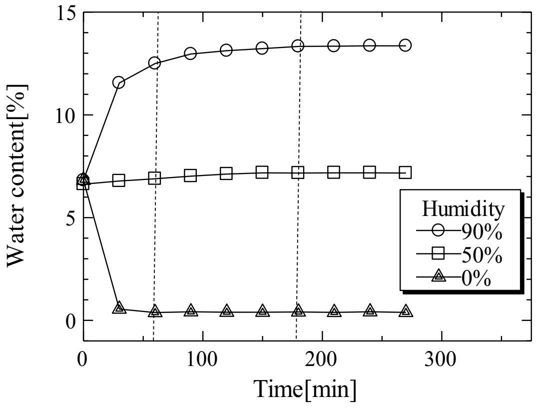

Fig. 4 Relationship between water content and treatment time

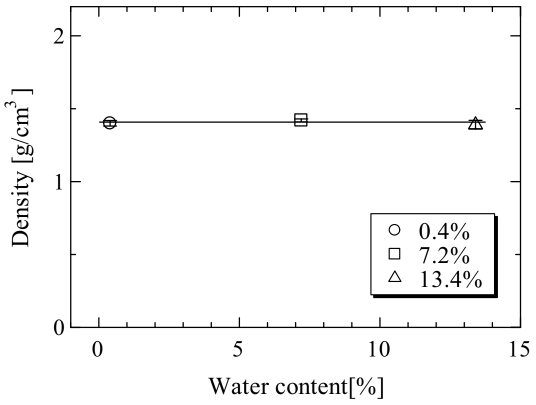

Fig. 6 Relationship between density and water content

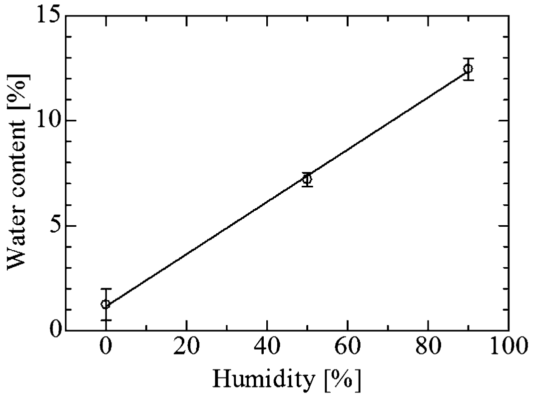

Fig. 5 Relationship between water content and humidity

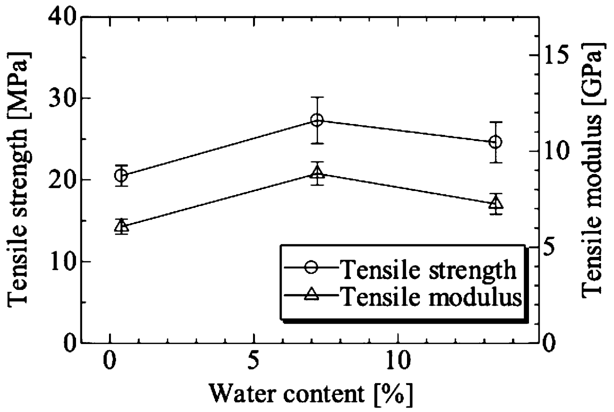

Fig. 7 Relationship between tensile strength, tensile modulus, and water content

3.1.2 Bamboo powder specimen

The specimens with water contents of 0.4, 7.2, and 13.4% molded at 200 °C exhibited a strong brown color. The surface specimens became glossy and solid-like plastics. Figure 6 indicates the relationship between the density of the bamboo powder product and water content. As shown, the density of the specimens remained largely the same with increasing water content. The density was in the range of 1.41–1.42 g/cm^3 and did not significantly change with water content.

3.1.3 Tensile properties of bamboo powder specimen

Figure 7 indicates the relationship between the tensile strength, tensile modulus, and water content of the bamboo powder. The highest value of tensile strength was 27.3 MPa at a water content of 7.2%. The minimum value was 20.5 MPa at a water content of 0.4%. As shown in Fig. 7, the highest value of the tensile modulus was 8.8 GPa at a water content of 7.2%. The minimum value was 6.1 MPa at a water content of 0.4%. The tensile modulus exhibited the same trend as that of the tensile strength. After the test, the fracture behavior of the state of breakage was observed. For the specimen molded at a water content of 0.4%, delamination and pull-out were observed between the parenchyma cells and the single fibers. At 7.2%, a single fiber fracture can be seen in a part of the specimen. Lignin affects the adhesion between single fibers and parenchyma cells (Jain et al. 1992), and the adhesive strength of lignin changes depending on the water content.

3.1.4 Flexural properties of bamboo powder specimen

Figure 8 presents the relationship between the flexural strength and modulus of the bamboo powder products and the water content. The maximum value of the flexural strength was 59.3 MPa at a water content of 7.2%. The minimum value was 53.4 MPa at a water content of 13.4%.

As is evident from Fig. 8, the maximum value of the flexural modulus was 10.4 GPa at a water content of 7.2%. The

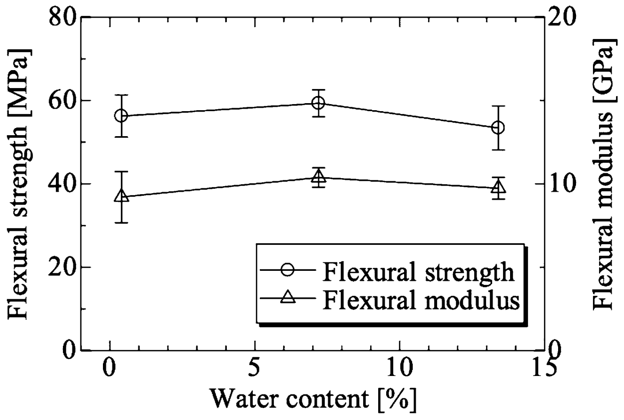

Fig. 8 Relationship between flexural strength and modulus and water content

minimum value was 9.2 MPa at a water content of 0.4%. The highest strength was observed at a water content of 7.2%, which was similar to the trend of the tensile strength. The highest strength following the appearance of fracture after the flexural test showed the same tendency as in the tensile test. The above results show that the bamboo powder products with a water content of 7.2% exhibited the highest strength. Thereafter, a strength test was performed using a test specimen with 7.2% water content.

3.2 Effects of molding temperature on mechanical properties of bamboo powder products

3.2.1 Bamboo powder specimen

Figure 9 presents the images of the surface of the bamboo powder specimen. The color of the surface of the bamboo powder product prepared at 160 °C was light yellow, but the color turned blackish with increasing molding temperature, and a strong brown color could be observed at 200 °C. This indicated that the bamboo powder product darkened due to carbonization between 160 and 200 °C.

As the molding temperature exceeded 200 °C, the bamboo powder turned black and stuck to the metallic mold. Therefore, 200 °C was determined to be the maximum temperature at which molding was possible. Figure 10 shows the relationship between the density of the bamboo powder products and the molding temperature. The density (1.42 g/cm^3) remained largely constant with increasing molding temperature.

3.2.2 Tensile properties of bamboo powder specimen

Figure 11 shows the relationship between the tensile strength, tensile modulus, and molding temperature. This figure indicates that both the tensile strength and tensile modulus increased with increasing molding temperature. The tensile strength and tensile modulus of the bamboo powder product prepared at 200 °C were 28.5 MPa and 8.4 GPa, respectively. Figure 12 shows the images of the fracture surface after the tensile strength test. In the bamboo powder product prepared at 160 °C, pull-out and delamination could be observed between the parenchyma cells and the single fibers. At 180 °C, a fracture of single fibers could be observed in a part of the specimen. In the case of the product prepared at the molding temperature of 200 °C, the single

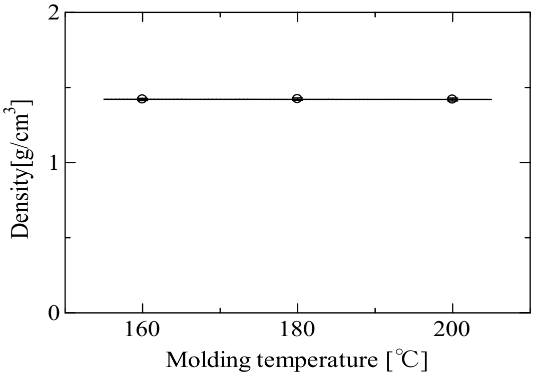

Fig. 10 Relationship between density and molding temperature

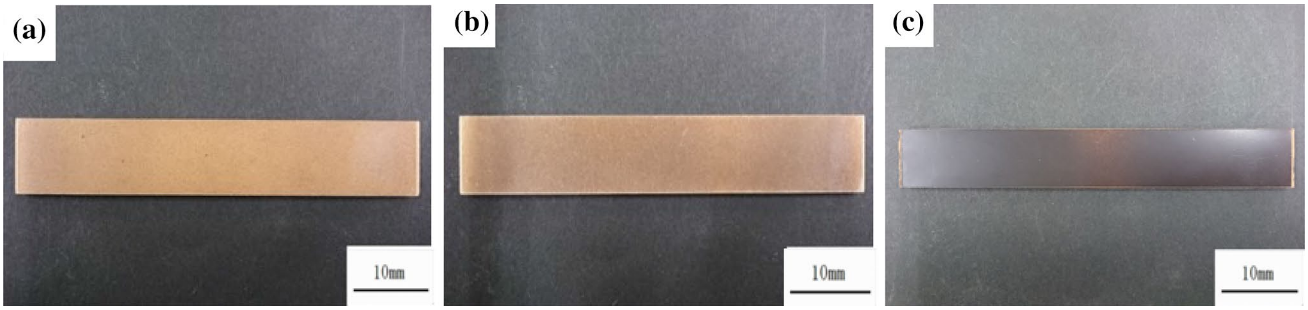

Fig. 9 Surface images of bamboo powder specimens molded at **a** 160 °C, **b** 180 °C, and **c** 200 °C

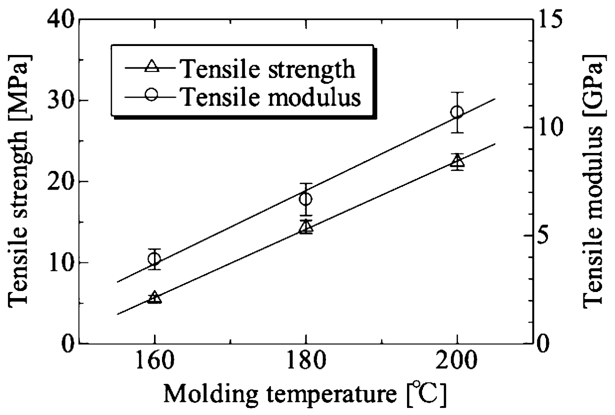

Fig. 11 Relationship between tensile strength, tensile modulus, and molding temperature

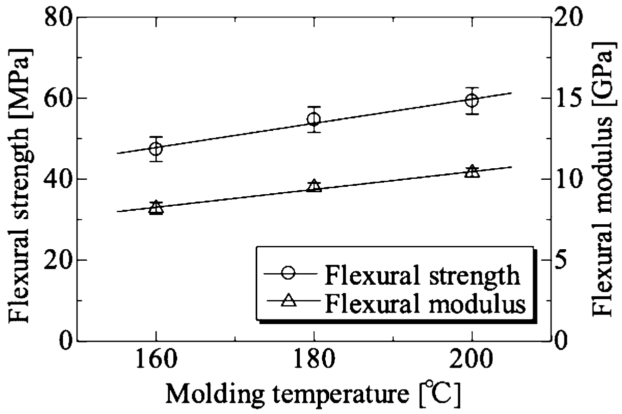

Fig. 13 Relationship between flexural strength, flexural modulus, and molding temperature

fibers fractured, and the parenchyma cells and single fibers were mixed homogeneously.

3.2.3 Flexural properties of bamboo powder specimen

Figure 13 shows the relationship between the flexural strength, flexural modulus, and molding temperature. This figure indicates that both flexural strength and flexural modulus increase with increasing molding temperature. The flexural strength and flexural modulus of the bamboo powder product prepared at 200 °C were 59.3 MPa and 10.4 GPa, respectively. Kajikawa and Iizuka (2015) injection-molded bamboo powder and investigated its mechanical properties. The powder showed bending strength of 36 MPa. In this study, the bending strength was 59.3 MPa. Moreover, it is believed that humidity control affected the increase in strength. The observation of the state after the flexural test showed that the tendency was similar to that after the tensile test. For the bamboo powder product made at 160 °C, pull-out and delamination could be observed between the parenchyma cells and the single fibers, and adhesion between the parenchyma cells and the single fibers was weak. At 180 °C, fracture of the single fibers could be observed in a part of the specimen. For the bamboo powder product made at 200 °C, it was difficult to identify single fibers, and the parenchyma cells and the single fibers mixed homogeneously.

The results of the mechanical tests demonstrate that in the case of a low molding temperature, the adhesive parts of the parenchyma cells and the single fibers are possible fracture locations. With increasing molding temperature, the adhesive strength of the parenchyma cells and the single fibers increase. When the molding temperature is low, a high strength can be achieved because the strength of a single fiber does not reduce. In this study, the bamboo powder product molded at a high temperature exhibited a high value. When specimens were fabricated at a low molding temperature, the adhesive strength between the parenchyma cells and single fibers was poor; this consequently induces locations where fractures begin. For the specimen made at high molding temperature, flaking off of the parenchyma cells and single fibers is not observed, and the adhesive strength is high. From these results, it can be said that the bond between the parenchyma cells and single fibers significantly influences the strength of the bamboo powder products owing to

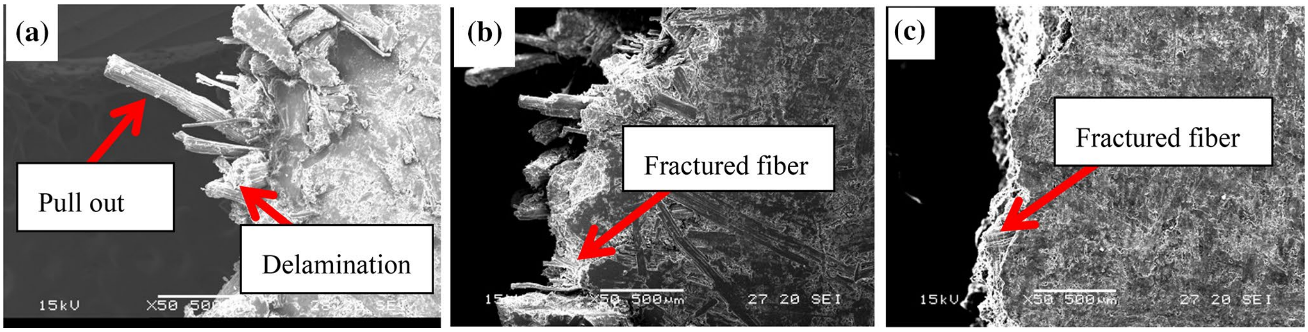

Fig. 12 Images of the fracture surface after tensile test of specimens molded at **a** 160 °C, **b** 180 °C, and **c** 200 °C

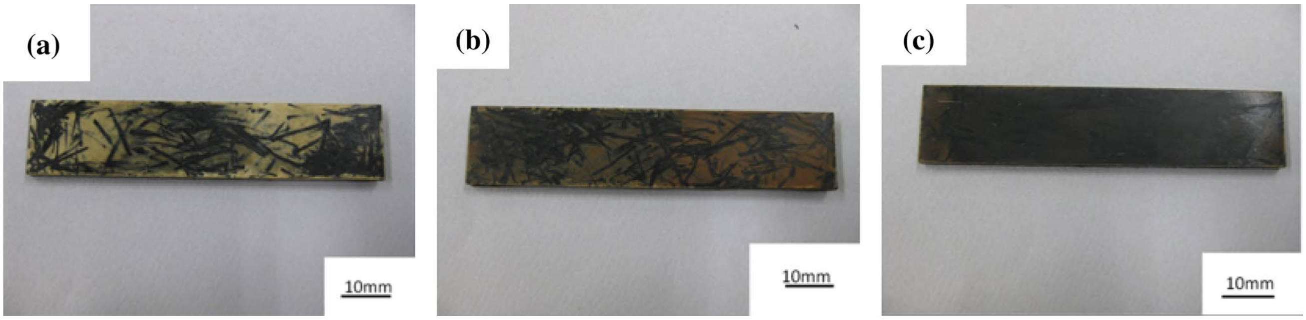

Fig. 14 Surface images of bamboo fiber bundle-reinforced bamboo powder specimens molded at **a** 160 °C, **b** 180 °C, and **c** 200 °C

the strength of the single fibers when the bamboo powder is fabricated by hot pressing.

3.3 Effects of fiber bundle content on mechanical properties

3.3.1 Bamboo fiber bundle-reinforced bamboo powder specimen

Figure 14 shows the surface images of bamboo fiber bundle-reinforced bamboo powder specimens prepared with a fiber content of 50%. The color of the bamboo fiber bundle-reinforced bamboo powder composite materials fabricated at 160 °C was light yellow, but the surface color darkened with increasing molding temperature, and a strong brown color was observed at 200 °C. This result suggests that the bamboo fiber bundle-reinforced bamboo powder composite materials browned due to carbonization between 160 and 200 °C. This tendency is the same as in the case of 100% bamboo powder.

Figure 15 shows the relationship between the density of bamboo fiber bundle-reinforced bamboo powder composite materials and the molding temperature. As shown, the density of the specimens remained largely the same as the molding temperature increased. The value was in the range of 1.41–1.42 g/cm^3. Figure 16 shows the relationship between the density of the bamboo fiber-reinforced bamboo powder composite materials and the fiber bundle content. The density of the specimens remained largely the same in the range of 1.41–1.42 g/cm^3 as the fiber bundle content increased. Based on these results, the density does not change with increasing molding temperature and fiber bundle content.

3.3.2 Tensile properties of bamboo fiber-reinforced bamboo powder specimen

Figure 17 presents the relationship between the tensile strength and tensile modulus of bamboo fiber bundle-reinforced bamboo powder composite materials (50% fiber bundle content) and molding temperature. As shown, the specimen molded at 180 °C had a higher strength (42.7 MPa) than that molded at 160 and 200 °C. Consequently, 180 °C was shown to be the most appropriate molding temperature. This was expected as the strength of the fiber bundle itself is known to decrease. The strength decreases in the case of natural fiber at high temperatures (Testa et al 1994; Gassan and Bledzki 2001). Furthermore, as shown in Fig. 17, the

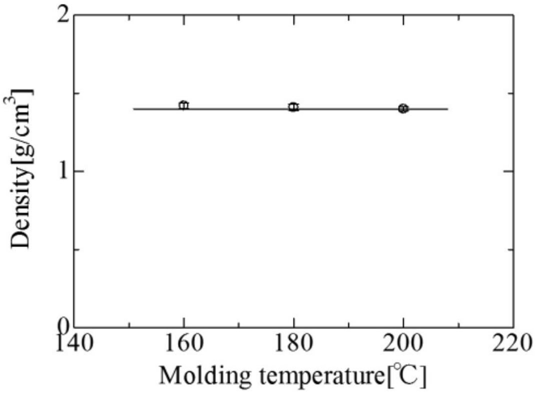

Fig. 15 Relationship between density and molding temperature (fiber content: 50%)

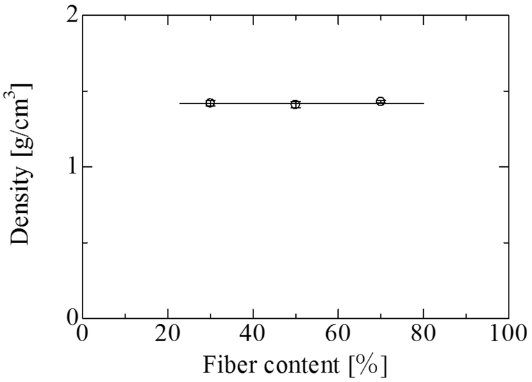

Fig. 16 Relationship between density and fiber content (molding temperature: 180 °C)

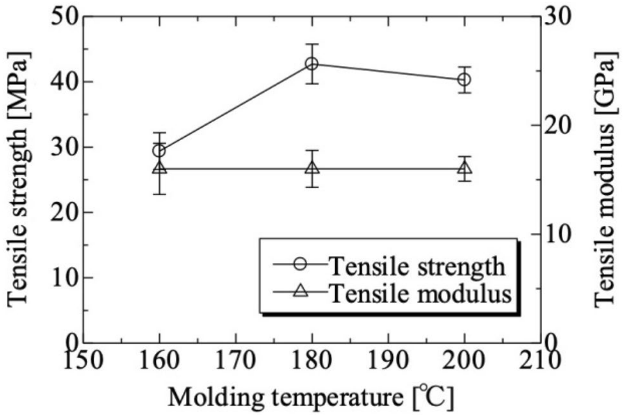

Fig. 17 Relationship between tensile strength and molding temperature (fiber content: 50%)

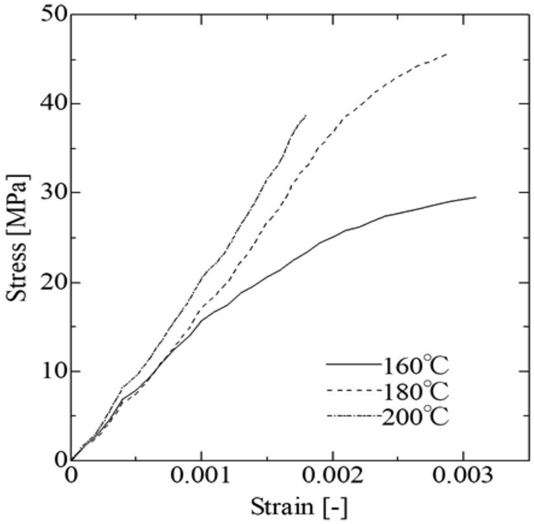

Fig. 18 Stress–strain diagram (fiber content: 50%)

tensile modulus of the specimens remained largely the same with increasing molding temperature. The tensile modulus of the composites was 16.6 GPa. Figure 18 shows an example of a stress–strain diagram. In the small region where the strain is less than 0.0005, the slopes are almost the same. However, a different tendency can be confirmed as the strain increases. The slope of the material with a molding temperature of 160 °C is smaller than 0.001, and that with a molding temperature of 180 °C is 0.002. Furthermore, from the figure, it can be confirmed that the material with a low molding temperature has a large elongation at break. Figure 19 shows the fracture surface after tensile testing. Fractures of the fiber bundles can be observed in the entire specimen. However, in the case of the bamboo fiber-reinforced bamboo powder composite materials prepared at 160 °C (Fig. 19a), delamination can be observed in the fiber bundles, and in the case of those prepared at molding temperatures of 180 and 200 °C, the bamboo powder and bamboo fiber bundle mix homogeneously. However, the tensile strength of the molded product at 200 °C decreased because of the decrease in the strength of the fiber bundle.

Figure 20 presents the relationship between tensile strength and tensile modulus of the bamboo fiber bundle-reinforced bamboo powder composite materials and the fiber bundle content of the specimen molded at 180 °C. The tensile strength increased linearly with the fiber bundle content. The tensile strength of the specimens with a fiber fraction of 70% was 45.0 MPa. According to the composite rule (Hull and Clyne 1996), the tensile strength of a composite material can be expressed as

$$\sigma = V_f\sigma_m + V_f\sigma_m, \tag{1}$$

where, σ is the strength of the composite material, σ_m and σ_f are the strengths of the matrix and fiber, respectively. V_m and V_f are the volumes of the matrix and fiber, respectively.

The strength of the unidirectionally reinforced composite material of glass fiber/epoxy resin (when the fiber content is 50%) is about 1000 MPa, and that of the random material

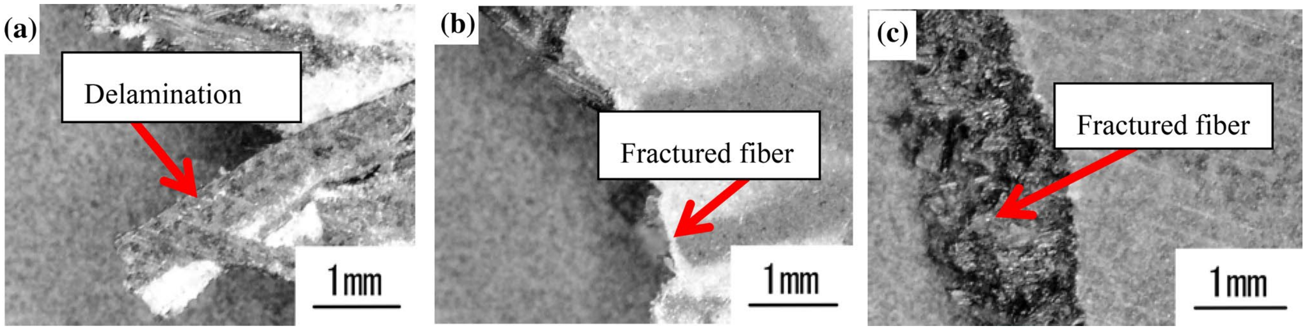

Fig. 19 Fracture surface of specimens molded at 160, 180, and 200 °C with a fiber content of 50%

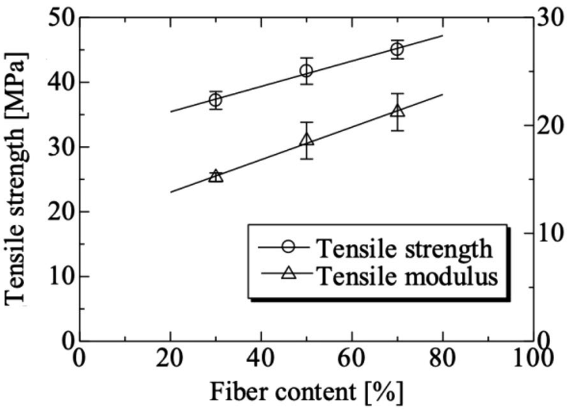

Fig. 20 Relationship between tensile strength and fiber content (temperature: 180 °C)

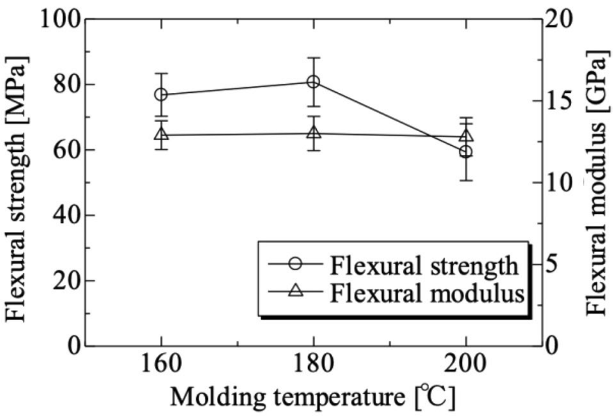

Fig. 21 Relationship between flexural strength, flexural modulus, and molding temperature (fiber content: 50%)

is about 160 MPa (Hull and Clyne 1996). When 160 MPa strength of random material is divided by 1000 MPa strength of unidirectional material, the ratio is about 16%. The strength of the bamboo fiber bundle used in this study is about 516 MPa, and that of the composite material (in the case of 50% fiber) is about 250 MPa. Dividing 40 MPa of strength of random material by the strength of 250 MPa of unidirectionally reinforced composite material of bamboo fiber gives a ratio of 16%. This is very similar to the value of fiberglass reinforced composites.

In addition, as evident from Fig. 20, the tensile modulus increases with increasing fiber bundle content. For the specimen molded with a fiber content of 70%, the tensile modulus was 21.2 GPa.

3.3.3 Flexural properties of bamboo fiber bundle-reinforced bamboo powder specimen

Figure 21 presents the relationship between the flexural strength and flexural modulus of bamboo fiber bundle-reinforced bamboo powder composite materials (50% fiber bundle content) and the molding temperature. The flexural strength increased slightly at molding temperatures ranging from 160 to 180 °C; however, at 200 °C, the strength of the bamboo fiber bundle-reinforced bamboo powder specimen decreased because of the decrease in the strength of the fiber bundle itself. As mentioned previously, the strength decreases in the case of natural fibers at high temperatures (Testa et al 1994; Gassan and Bledzki 2001). In their research on the molding materials for cedar and cypress, Miki et al. (2003) found that the molding temperature of 180 °C yielded the best mechanical properties, which decreased with increasing temperature. Their results were similar to those of bamboo in this study. As is evident from Fig. 21, the flexural modulus of the specimens remained largely constant at 13 GPa with increasing molding temperature. The observation of the state after the strength test showed a tendency similar to that after the tensile test shown in Fig. 19. Fractures of the fiber bundles could be observed in the entire specimen. However, bamboo fiber bundle-reinforced bamboo powder composite materials prepared at 160 °C showed delamination of the fiber bundles. When the specimens were molded at 180 °C and 200 °C, the bamboo powder and fiber bundle mixed homogeneously; however, the flexural strength at 200 °C of the molded product decreased because of the decrease in the strength of the fiber bundle.

As shown in Fig. 21, the specimen molded at 180 °C had a higher strength than that molded at 160 and 200 °C. Consequently, 180 °C was shown to be the most appropriate temperature. Figure 22 shows an example of a stress–strain diagram. The slope is almost the same at small strains but changes when the strain is large. Furthermore, it can be confirmed that the material with a low molding temperature has a large elongation at break. This is the same as in the case of tensile testing. Figure 23 presents the relationship between the flexural strength, flexural modulus, and fiber bundle content of a bamboo fiber bundle-reinforced bamboo powder composite material prepared at 180 °C. As shown, the flexural strength increased linearly with increasing fiber bundle content. The flexural strength of the samples with a fiber fraction of 70% was 101.4 MPa.

In addition, as shown in Fig. 23 the flexural modulus increased with increasing fiber bundle content. For the specimen molded at a fiber content of 70%, the flexural modulus was 13.3 GPa. The highest strength was obtained at a fiber bundle content of 70%, which was consistent with the results of the tensile tests. When the fiber bundle content was 70%, the maximum strength and elastic modulus showed the same tendency as the tensile properties. From the above results, it is clear that the highest strength was obtained at the fiber bundle content of 70% and molding temperature of 180 °C.

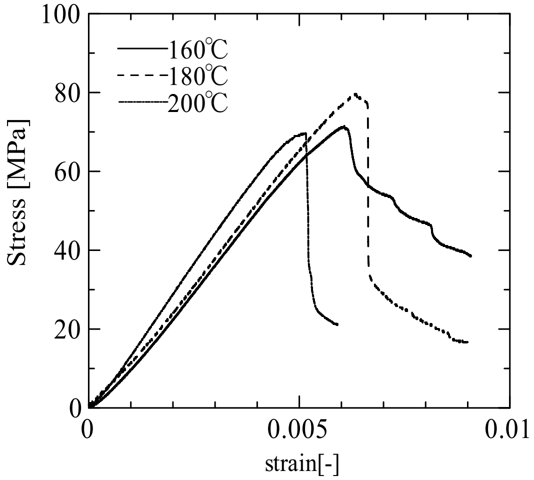

Fig. 22 Stress–strain diagram (fiber content: 50%)

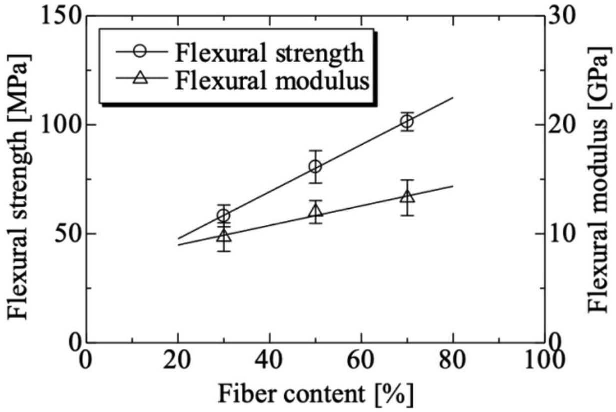

Fig. 23 Relationship between flexural strength, flexural modulus, and fiber content (molding temperature: 180 °C)

Lokesh et al. (2019) investigated the mechanical properties of composite materials prepared with bamboo fiber and epoxy resin. They reported a tensile strength of 18 MPa and bending strength of 40 MPa. Furthermore, Harikumar and Devaraju (2020) studied the mechanical properties of bamboo fiber composite added with Al_2O_3 nanoparticles. They reported a tensile strength of 33.5–40.3 MPa and bending strength of 40.3–45.2 MPa. The corresponding values in this study are higher than the abovementioned values, and it can be said that the reinforcement with bamboo fiber bundles obtained using the steam explosion method is excellent.

3.4 Comparison with common plastics

Table 4 lists the density, tensile properties, and flexural properties of common plastics, bamboo powder products, and the bamboo fiber bundle-reinforced bamboo powder composite materials. The density of the bamboo powder products and bamboo fiber bundle-reinforced bamboo powder composites was the same as that of polyacetal (POM). The tensile strength of polyvinyl chloride (PVC) is in the range of 40.7–51.8 MPa. The tensile strength (45.0 MPa) of the press-molded product using 70% bamboo fiber molded at 180 °C was close to that of PVC. The flexural strengths of POM and PVC are in the ranges of 100–110 MPa and 69–110 MPa, respectively. The flexural strength (101.4 MPa) of the press-molded product using 70% bamboo fiber molded at 180 °C was close to that of POM and PVC. These results suggest the possibility of effectively replacing conventional products with bamboo bundle/powder composites.

4 Conclusion

This study was aimed to establish the molding conditions for high-strength bamboo composite materials. First, the effect of molding temperature and water content on the strength of bamboo powder products was examined. Next, the effect of molding temperature and fiber bundle content on the strength of bamboo fiber bundle-reinforced composite materials was examined. The following conclusions were drawn:

1. The density of the bamboo powder product was in the range of 1.41–1.42 g/cm^3. This value was equivalent to that of POM, which is an engineering plastic. The density did not change with the molding temperature and water content. In addition, the density of the bamboo fiber bundle-reinforced bamboo powder composite materials did not change with increasing molding temperature and fiber content.
2. The effects of water content on the tensile and flexural properties of bamboo powder products were investigated. Under the conditions of this study, bamboo powder product with a water content of 7.2% exhibited the highest tensile and flexural strengths. This is presumed to be due to the fact that lignin affects the adhesion between single fibers and parenchyma cells, and the adhesive strength of lignin varies depending on the water content.
3. The tensile strength and flexural strength of the 100% bamboo powder product increased linearly with increasing molding temperature. The tensile strength and flexural strength of the bamboo powder product prepared at 200 °C were 28.5 and 59.3 MPa, respectively. This was because the adhesive strength between the single fiber and the powder is weak, and pullout of the single fiber is observed at the molding temperature of 160 °C. Further, the adhesive strength between the single fiber and powder is strengthened at 200 °C, and the fiber breaks.
4. The tensile strength and flexural strength of the bamboo fiber bundle-reinforced bamboo powder compos-

Table 4 Density and tensile and flexural properties of common plastics (Osswald and Menges 2003) and bamboo fiber bundle-reinforced bamboo powder composite materials

	Density (g/cm^2)	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
PE	0.95–0.97	22.1–33.1	1.1	33.0	1.0–1.6
PP	0.89–0.91	27.6–38.0	0.9–1.2	34.5–48.3	0.9–1.4
POM	1.42	67–69	2.6–3.6	90–110	2.6–3.4
PVC	1.30–1.58	40.7–51.8	2.4–4.1	69–110	2.1–3.5
PC	1.2	63–72	2.4	83–97	2.3–2.4
160 °C×0%	1.42	10.4	2.1	47.4	8.2
180 °C×0%	1.42	17.8	5.4	54.7	9.7
200 °C×0%	1.42	28.5	8.4	59.3	10.4
160 °C×50%	1.42	29.4	16.5	76.8	12.9
180 °C×30%	1.42	37.2	15.2	58.2	9.7
180 °C×50%	1.41	42.7	16.6	80.7	13.0
180 °C×70%	1.42	45.0	21.2	101.4	13.3
200 °C×50%	1.41	40.3	16.4	59.3	12.8

Molding temperature × bamboo fiber bundle content (bamboo fiber bundle-reinforced bamboo powder composite materials)

PE polyethylene, *PP* polypropylene, *POM* polyacetal, *PVC* polyvinyl chloride, *PC* polycarbonate

ites increased at temperatures ranging from 160 to 180 °C, but decreased at 200 °C. The tensile and flexural strengths of the composite materials decreased because of a decrease in the strength of the fiber bundle itself. Consequently, 180 °C was indicated to be the most appropriate molding temperature in terms of fiber bundle reinforcement. Under the conditions of this study, the bamboo fiber-reinforced bamboo powder composites molded at 180 °C exhibited the highest tensile and flexural strengths of 45.0 and 101.4 MPa, respectively.

5. The tensile strength of the bamboo fiber bundle-reinforced bamboo powder composite materials was equivalent to that of PVC, and the flexural strength of the composite was equivalent to that of general-purpose engineering plastics such as PVC and POM. The bamboo fiber bundle/bamboo powder composites produced in this work have strengths comparable to those of engineering plastics, and it may be possible to apply them practically by clarifying other values such as impact strength and heat resistance. As this product does not use petroleum as a raw material, it does not produce harmful gases even when it is discarded; moreover, it is a material that can be easily reproduced. To enable practical use of this material in future, the mechanical properties such as pull-out test of fiber, hardness, impact, and compression must be investigated.

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