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Development and mechanical properties of bagasse fiber reinforced composites

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Development and mechanical properties of bagasse fiber reinforced composites

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Abstract—Environment-friendly composites reinforced with bagasse fiber (BF), a kind of natural fiber as the remains from squeezed sugarcane, were fabricated by injection molding and press molding. As appropriate matrices for injection molding and press molding, polypropylene (PP) and polycaprolactone-cornstarch (PCL-C) were selected, as a typical recyclable resin and biodegradable resin, respectively. The mechanical properties of BF/PP composites were investigated in view of fiber mass fraction and injection molding conditions. And the mechanical properties and the biodegradation of BF/PCL composites were also evaluated. In the case of injection molding, the flexural modulus increased with an increase in fiber mass fraction, and the mechanical properties decreased with an increase in cylinder temperature due to the thermal degradation of BF. The optimum conditions increasing the flexural properties and the impact strength were 90°C mold temperature, 30 s injection interval, and in the range of 165 to 185°C cylinder temperature. On the other hand, as to BF/PCL-C fully-green composites, both the flexural properties and the impact strength increased with an increase in fiber mass fraction. It is considered that the BF compressed during preparation could result in the enhancement in mechanical properties. The results of the biodegradability test showed the addition of BF caused the acceleration of weight loss, which increased further with increasing fiber content. This reveals that the addition and the quantities of BF could promote the biodegradation of fully-green composites.

Keywords: Bagasse fiber; biocomposite; fully-green composite; biodegradable resin; mechanical property; biodegradation; injection molding; press molding.

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1. INTRODUCTION

Natural fibers have proved to be a renewable and cheaper substitute than synthetic fibers such as glass and carbon, which are traditionally used as reinforcements in the applications of structural components. The advantages of natural fibers are their acceptable specific strength and stiffness properties, low cost and low density. Particularly, they are relatively more abundant in nature and more eco-friendly in contrast to their opponents. Thus, natural fibers such as jute, sisal, pineapple, abaca and coir [1–8] have been studied as reinforcements of fiber-reinforced composites to clarify their fundamental and practical properties. On the other hand, some kinds of natural fibers cause disposal problems, such as fibrillar shells after eating coconuts, and bagasse fibers (BF) produced from the remains of squeezed sugarcane. Viewing the advanced application of these fibers, BF may be applied as reinforcement for fiber-reinforced composites along with thermoplastic resins such as polypropylene (PP). Furthermore, fully-green composites, completely biodegradable resin matrix composites reinforced with natural fibers, have recently attracted the attention of scientists and engineers, and many studies have been made to develop these composites for various applications [2, 3, 7]. Fully-green composites composed of BF and biodegradable resin polycaprolactone-cornstarch (PCL-C) may also be studied from the social demand of environment-friendly material.

Thus, this paper describes the fabrications of composites consisting of BF and PP by injection molding, and fully-green composites made from BF and PCL-C by press molding, respectively. The mechanical properties of BF/PP composites were investigated in terms of fiber mass fraction and injection molding conditions. In addition, the mechanical properties and the biodegradation of BF/PCL-C composites were examined from the point of view of fiber mass fraction. Thermogravimetric analysis (TGA) of BF was performed to assess the fiber thermal properties, and scanning electron microscope (SEM) studies were made to show the impact fracture surface and the surface morphology of composites before and after biodegradability test.

2. EXPERIMENTAL

2.1. Materials

The thermoplastic resin, PP (Noblen AZ864N), was supplied from Sumitomo Chemical Co. Ltd. (Tokyo, Japan). The biodegradable resin, PCL-C (Randy CP-300), was a cornstarch-based resin, which is a blend of PCL and cornstarch, supplied from Miyoshi Oil and Fat Co. Ltd. (Nagoya, Japan). This emulsion resin was dried at 105°C to vaporize the water, and then cut into pellets of 1.5 to 2 mm in diameter. The properties of PP, PCL-C and BF are shown in Table 1.

Table 1.
Properties of polypropylene, polycaprolactone-cornstarch and bagasse fiber

	Tensile strength (MPa)	Average diameter (mm)	Average length (mm)	Density (kg/m^3)	Young's modulus (MPa)
Polypropylene	24	–	–	902	1315
Polycaprolactone-cornstarch	10.6	–	–	1160	531
Bagasse fiber	70.85	0.49	9.13	–	–

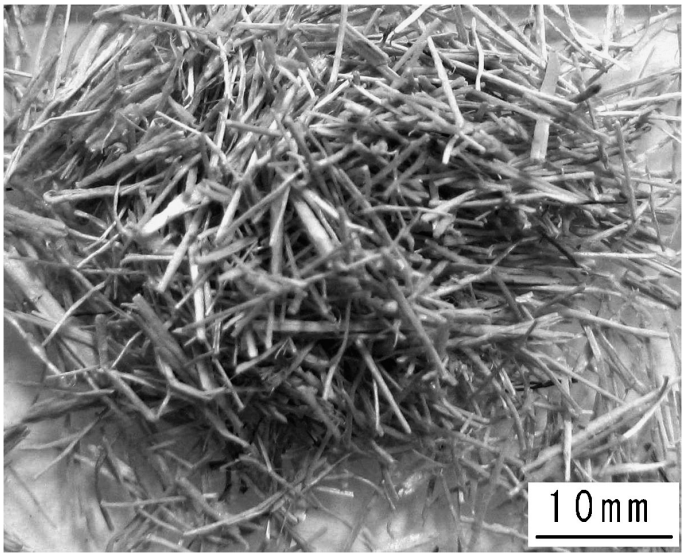

Figure 1. Bagasse fibers.

Bagasse was obtained as the leftover after liquor extraction in a sugar mill, and then was dried for 72 h at 80°C. After being dried and crushed, the needle-like BF were produced, which look like glass fibers as shown in Fig. 1.

2.2. Fabrication of composites

BF and PP were compounded and kneaded with a double arm mixer (type S5–2, Moriyama Co. Ltd., Japan) at 190°C for 1 h in air. Four kinds of compounds with different fiber mass fractions 10, 20, 30 and 40% were prepared for the fabrication of composites. Then, the compound was pulverized with the mixer for 6 h into pellets (2 to 5 mm in diameter) during cooling. The pellets were molded to composites by an injection molding machine (PS10E1ASE, Nissei Co. Ltd., Japan). The injection molding conditions used are listed in Table 2. The fabricated composites were of cylindrical shape, 60 mm in length and 5.8 mm in diameter.

Fully-green composites composed of BF and PCL-C were fabricated with a hot press (Type 2426, Marumoto Struers K. K., Japan). A steel mold was designed to

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Table 2.
Injection molding conditions

Injection pressure (MPa)	Cylinder temperature (°C)	Injection interval (s)	Mold temperature (°C)	Screw rotation speed (rev/min)
11	165–260	30, 180	30, 90	50

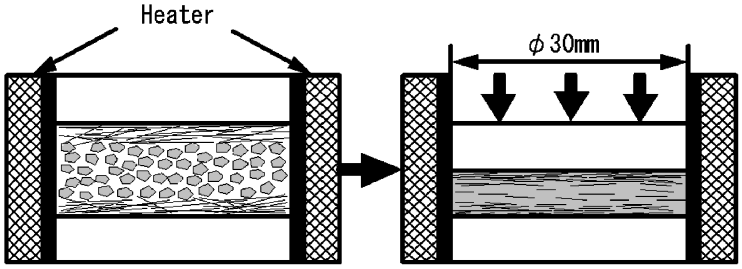

Figure 2. Schematic of preparation of fully-green composites.

prepare the composites with the diameter of 30 mm. As seen from Fig. 2, a half of the prescribed quantities of BF were first put into the mold, and then the matrix resin and the rest of the fibers were added subsequently. When the mold was heated to 160°C, the mixture was pressed under 10 MPa for 10 min. The composites reinforced with different fiber mass fractions (20, 35, 50, 60, 65%) were prepared for examination. The specimens (30 mm × 15 mm × 2 mm) were cut from the obtained composites for the mechanical properties and the biodegradability test.

2.3. Biodegradability test of fully-green composites

The experiment was performed in a series of plastic boxes containing characterized soil, which was 1:1 (mass ratio) mixture of red gravel soil and leaf mold for gardening. Each specimen was buried at a depth of 8 cm from the surface in the soil. Water was supplied at intervals of 2 days to keep the soil humid. At 4-week predetermined intervals, the specimens were removed from the soil, carefully washed with water and dried at 50°C to reach a constant weight. The specimens were weighed in order to determine the weight loss, which was used to evaluate the biodegradation.

2.4. Measurements

Three-point flexural tests were carried out using an Autograph DCS-R-100 (Shimadzu Co. Ltd., Japan) according to the standard method (ISO 178) used for plastics-determination of flexural properties. As to BF/PP composites, the span length and a cross-head speed were 55 mm and 1 mm/min, respectively. Regarding BF/PCL-C composites, the span length was 18 mm and the cross-head speed was

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1 mm/min. Five specimens for each condition were tested and then the mean values were calculated.

Charpy impact tests were carried out using a U-F Impact Tester (Ueshima Seisakusyo Co. Ltd., Japan) using the standard method for plastics-determination of Charpy impact strength (ISO 179), with a hammer weight of 0.6 kg and a falling height of 0.325 m. The impact strength was calculated as a mean value from five specimens.

TGA of BF was carried out using a Thermo Plus TG8120 (Rigaku Co. Ltd., Japan) under air atmosphere. The temperature profile was from 30 to 450°C at a heating rate of 10°C/min. The amount of sample used was approximately 6 mg.

Digital pictures were taken by a digital camera (Coolpix 9100, Nikon Co., Japan) for observation of the composites surface before and after burial. The morphology of BF and the fracture surface of composites were observed using a SEM (WS-250, Topcon Co., Japan). All samples were sputter coated with gold to provide enhanced conductivity, and were studied with the microscope operating at 15 or 30 kv.

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3. RESULTS AND DISCUSSION

3.1. Effects of fiber mass fraction and mold temperature on mechanical properties of BF/PP composites

At injection molding conditions of 165°C cylinder temperature, 30 s injection interval and 30 and 90°C mold temperatures, the BF/PP composites with different mass fractions were prepared. Figure 3 shows their mechanical properties as a function of fiber mass fraction at 30 and 90°C mold temperature. With an increase in fiber mass fraction, the flexural modulus increased, whereas the flexural strength is almost constant and the impact strength decreased observably. Compared with the mechanical properties of the composites prepared at 30°C mold temperature, the flexural strength and modulus at 90°C was 5–15% higher, meanwhile the impact strength hardly varied.

Surfaces of the composites made at different mold temperatures were observed. As seen in Fig. 4(a), some white parts presented a coarse appearance. In addition, it is obvious that some fibers departed from the resin. In contrast, at 90°C mold temperature, Fig. 4(b) displays a smooth appearance. When the materials were injected into the mold, it is considered that the low mold temperature would cause an insufficient flow of the materials. This leads to more defects in the composites and hence results in the low flexural strength and modulus.

3.2. Effects of cylinder temperature and injection interval on mechanical properties of BF/PP composites

As an important parameter in injection molding conditions, cylinder temperature should be higher than the crystalline temperature of PP resin, and lower than the

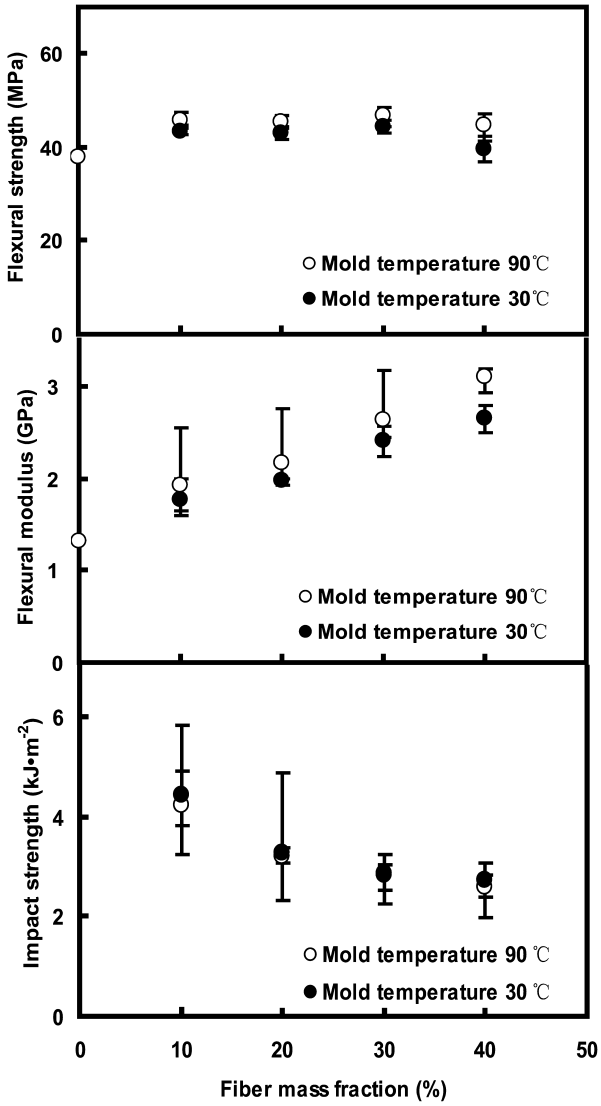

Figure 3. Mechanical properties of BF/PP composites as a function of fiber mass fraction at 30 and 90°C mold temperature.

thermal degradation temperature of BF. Here, the cylinder temperature was changed from 165 to 260°C, the injection interval was set at 30 or 180 s, respectively; as the other invariable conditions, the mold temperature was 90°C and the fiber mass fraction was 40%. Under the above conditions, the composites were prepared and the effects of cylinder temperature and injection interval on mechanical properties were investigated. The results are shown in Fig. 5. Both the flexural strength and modulus show maximum value at 185°C cylinder temperature, and then tended toward lower values over 185°C. On the other hand, the impact strength shows

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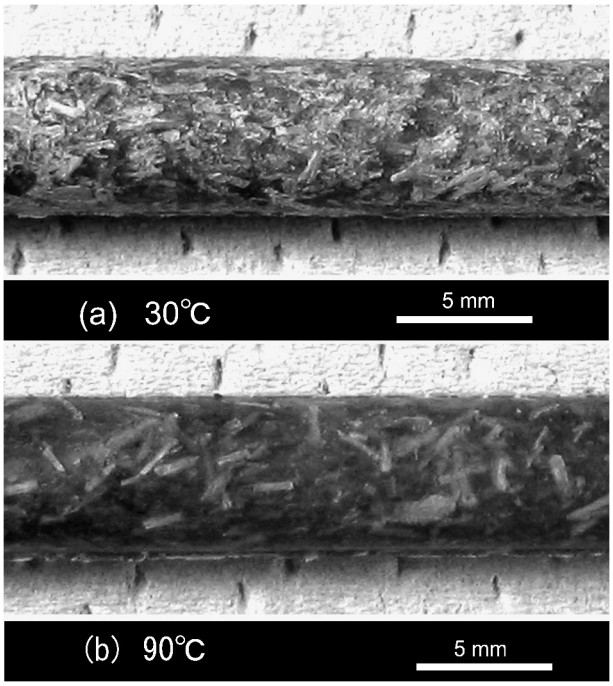

Figure 4. Appearances of BF/PP composites prepared at different mold temperatures.

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maximum value at 165°C and then began to decrease with an increase in cylinder temperature. The influence of different injection intervals on mechanical properties was evident. That is to say, almost all the mechanical properties of the composites fabricated at 180 s interval were lower than those at 30 s; in particular, the impact strength obviously decreased.

Figure 6 displays the appearances of the composites prepared at different cylinder temperatures. As the cylinder temperature was increased, the appearances were changed gradually. It was found that, moreover, the fiber size in the composite made at 260°C became smaller than that at other temperatures. These reveal that damage to fibers might increase at higher temperature. Figure 7 gives the TG curve of BF. Similar to the studies [9, 10], BF showed three stages of weight loss. The first stage was a slight decrease in weight, which was due to water evaporation, which continued up to about 120°C. The second stage started at 207°C. It is considered that this stage resulted from the generation of noncombustible gases such as CO_2 and formic and acetic acids. The third stage began at about 300°. This occurred because of the pyrolysis as well as generation of combustible gases. TG analysis indicates that the thermal degradation temperature of BF is 207°C and that, as such, the fibers could be effectively used as reinforcement below this temperature. Consequently, cylinder temperatures higher than 207°C lower the effect of fiber reinforcement owing to the fiber thermal degradation, and thus decrease the mechanical properties.

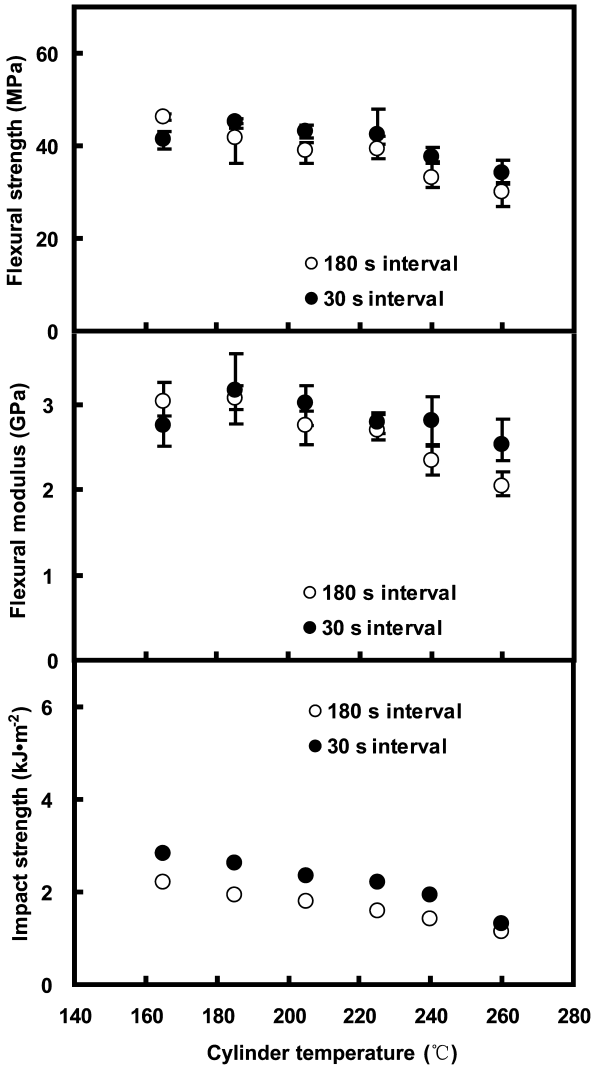

Figure 5. Mechanical properties of BF/PP composites as a function of cylinder temperature at 30 and 180 s injection interval.

Figure 8(a) is the SEM micrograph of an impact fracture surface of the composite made at 165°C and shows that the fibers were pulled out from the matrix and some holes remained. In contrast, Fig. 8(b) reveals that more holes were present on the fracture surface of the composite made at 260°C. Here, some holes shown in Fig. 8(a) and (b) might remain after pulled-out fibers; others in Fig. 8(b) occurred as a result of the generation of gases during the fiber thermal degradation. More holes lead to more defects in the composite, and therefore lower the mechanical properties, as shown in Fig. 5. Thus, the optimum injection conditions for BF/PP

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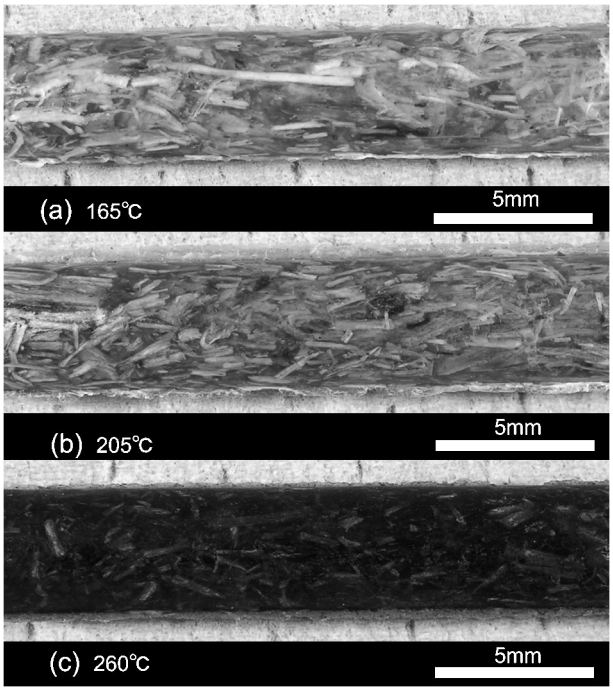

Figure 6. Appearances of BF/PP composites prepared at different cylinder temperatures.

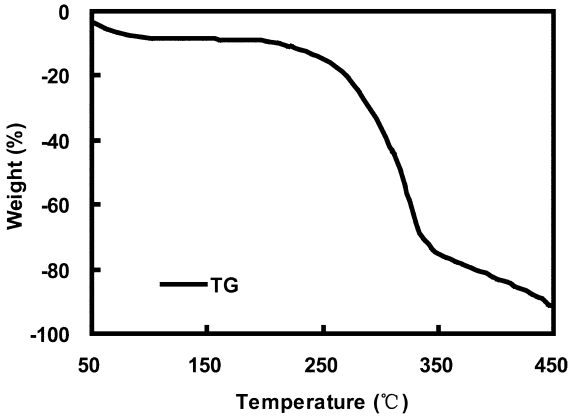

Figure 7. TG curve of bagasse fiber.

composites are 90°C mold temperature, 30 s injection interval, and in the range of 165 to 185° cylinder temperature.

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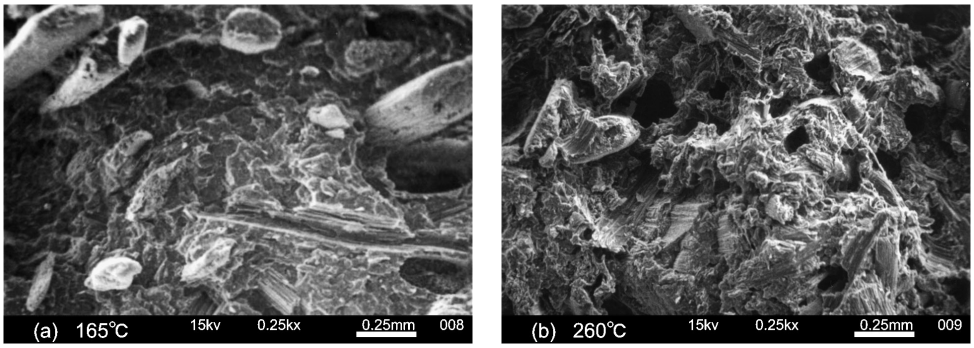

Figure 8. SEM micrographs of the impact fracture of BF/PP composites prepared at different cylinder temperatures.

3.3. Effect of fiber mass fraction on mechanical properties and biodegradation of BF/PCL-C composites

Figure 9 presents mechanical properties as a function of fiber mass fraction. Both the flexural properties and the impact strength increased with an increase in fiber mass fraction. Maximum values of 44 and 2.29 GPa for the flexural strength and modulus, and 9 kJ/m^2 for the impact strength were observed at 65%. The morphology of the fibers before and after preparation was studied by SEM. Figure 10(a) is the SEM micrograph of the cross-section of a raw BF, exhibiting the cellular structure of the fiber. Figure 10(b) displays the impact fracture surface of a fiber in the composite. The latter reveals a compressed cellular structure during preparation. The void fraction of the fiber decreased and the cellular structure became more rigid and denser due to the compression, leading to the enhancement in the mechanical properties of the fiber. Image analysis of the fiber cross-section showed the porous section occupying about 75–80% by volume, so it might be estimated that the mechanical properties of the compressed fiber would increase 4 times and more. Thus it is considered that the fiber compression could result in the enhancement in the mechanical properties, the potential of which should be noted in natural fiber reinforced composites.

Since the outstanding property of fully-green composites is their complete biodegradability, it is necessary that this biodegradation should be ascertained for future application. The weight losses of neat resin PCL-C, and the composites reinforced with 20 and 60% fiber mass fractions (20% BF/PCL-C and 60% BF/PCL-C) were measured as a function of degradation time during soil burial, as shown in Fig. 11. In comparison with the weight loss of PCL-C only being about 6% after 40 weeks, the weight loss of 20% BF/PCL-C increased to 12%, and further increased drastically to 31% in 60% BF/PCL-C. In other words, the addition of BF could cause the acceleration of the biodegradation of composites, and increase further with an increase in fiber content. Another remarkable point is that the biodegradation had hardly been observed in both neat resin PCL-C and 20% BF/PCL-C in first eight weeks, while 60% BF/PCL-C had already biodegraded in

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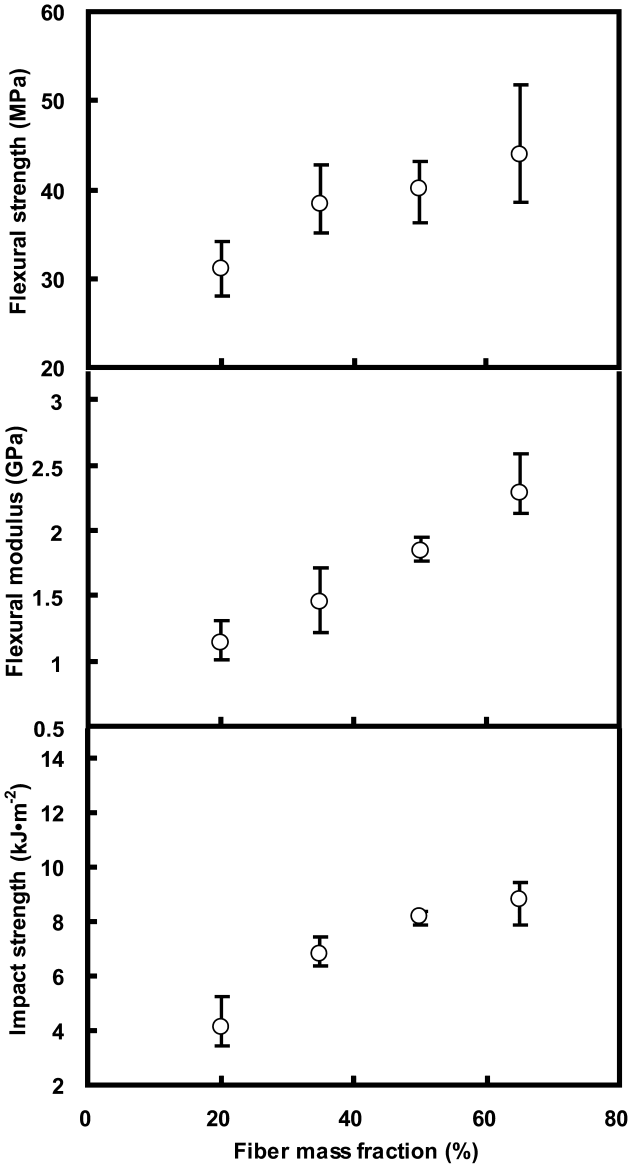

Figure 9. Mechanical properties of BF/PCL-C composites as a function of fiber mass fraction.

the first four weeks. The acceleration of biodegradation caused by adding plant-based natural fibers was also verified in PCL-C matrix composites reinforced with Manila hemp fibers [11].

Figure 12(a)–(f), displays the surface morphology of neat resin and the composites before (Fig. 12(a), (c) and (e)) and after (Fig. 12(b), (d) and (f)) burial. After 40 weeks burial, some black mildew and some small cavities appeared partly on the surface of PCL-C (Fig. 12(b)), indicating that the biodegradable resin shows some

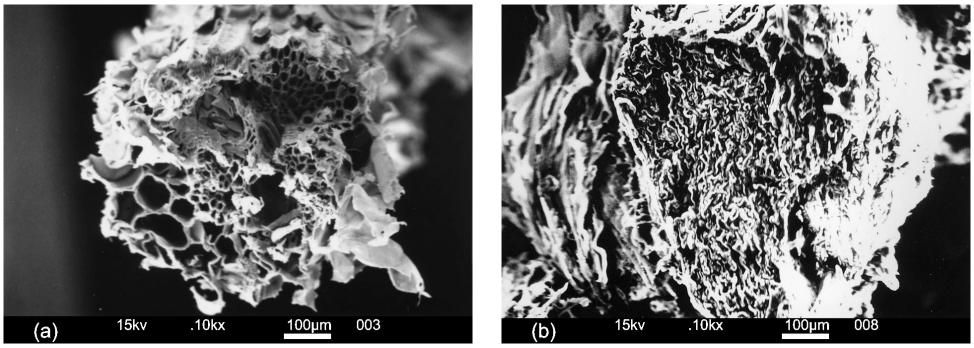

Figure 10. SEM micrographs of the cross section of a bagasse fiber. (a) Raw fiber. (b) Compressed fiber on the fracture surface of the composite.

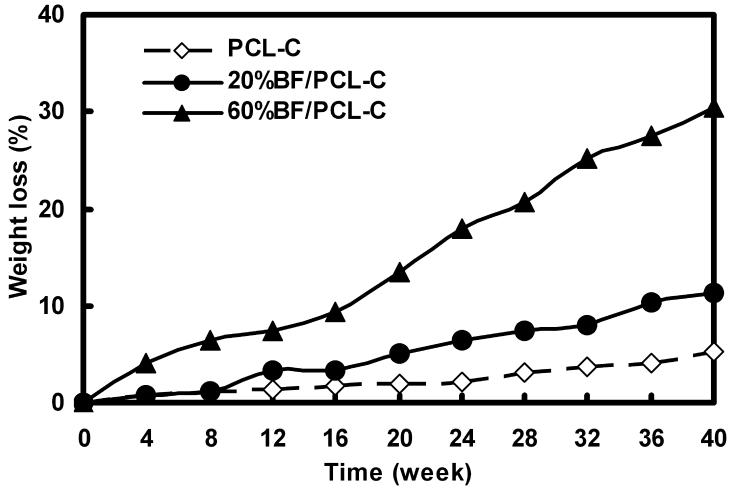

Figure 11. Weight loss of PCL-C and BF/PCL-C composites as a function of degradation time during soil burial.

biodegradability. As seen from Fig. 12(d), 20% BF/PCL-C shows a rough surface and some fibers had departed from the resin visibly. It is considered that added fibers and their interfaces could act as channels to promote the water entrance and diffusion from the surface to the inside of the composites, and serve as a support for the attack of microorganisms. Hence the addition and biodegradation of the fibers may contribute to higher weight loss in the composites. In the case of 60% BF/PCL-C, Fig. 12(f) reveals the BF were eroded and the resin around the fiber was removed rapidly, a rougher surface appeared and the composites became thinner in depth than that exhibited in Fig. 12(d). The same observation was found in SEM microphotographs. Different extents of the biodegradation in various composites were obvious. Compared with some resins being removed to a certain extent as shown in Fig. 13(a), Fig. 13(b) presents the exposed fibers and the removal of resin around the fiber, demonstrating that the fiber could promote the biodegradation

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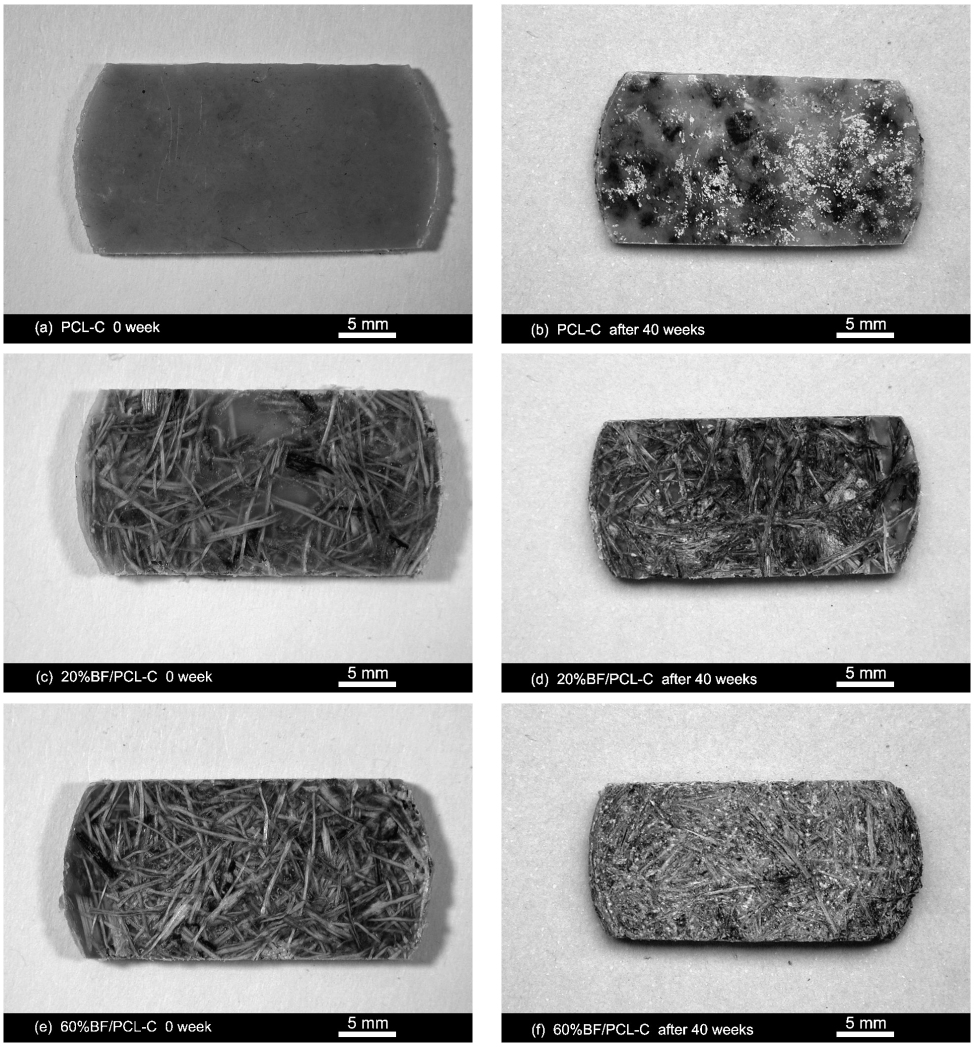

Figure 12. Photographs of PCL-C and BF/PCL-C composites buried for prescribed periods.

of resin around the fiber as well. Figure 13(c) illustrates the resin around the fiber degraded to graininess and the fibers were eroded on the surface. Thus, it is considered that the biodegradation proceeded more rapidly from the surface to the inside of the composites as a consequence of higher fiber content.

4. CONCLUSIONS

The mechanical properties and the biodegradation of BF reinforced composites were investigated. The obtained results are the following.

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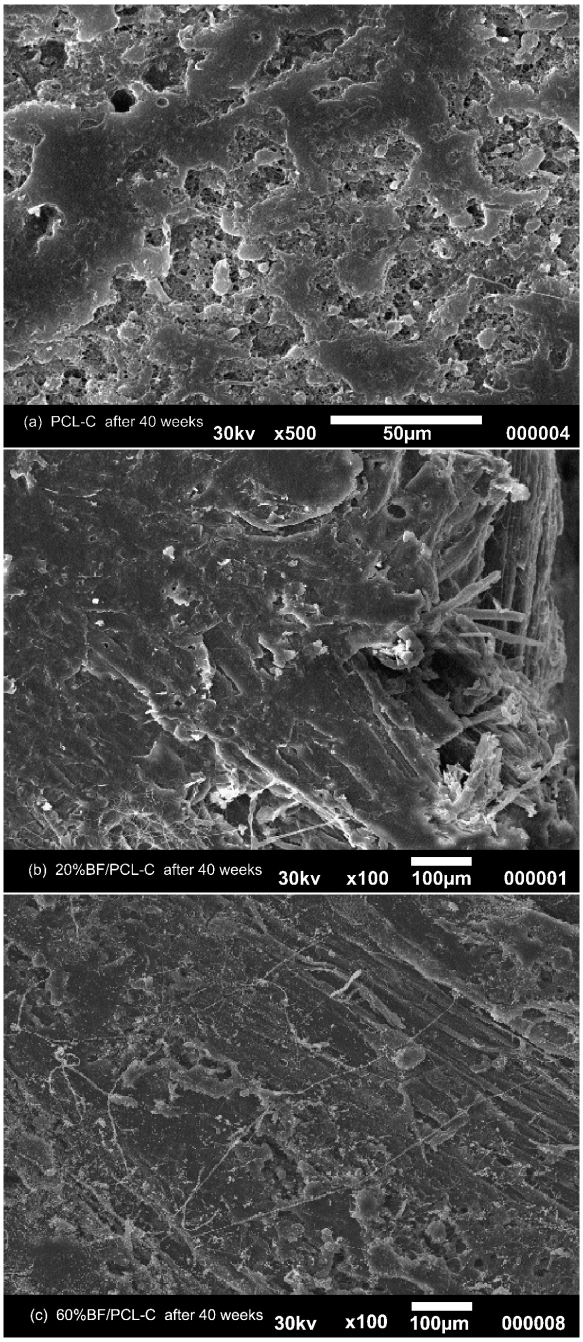

Figure 13. SEM Photographs of the surface of PCL-C and BF/PCL-C composites buried after 40 weeks.

Regarding BF/PP composites fabricated by injection molding, with an increase in fiber mass fraction, the flexural modulus increased, whereas the flexural strength did not change so significantly and the impact strength decreased. The mechanical properties showed a decreasing tendency with an increase in cylinder temperature. This might be due to the thermal degradation of BF. The maximum values of the flexural properties and the impact strength were found at 90°C mold temperature, 30 s injection interval, and in the range of 165 to 185°C cylinder temperature.

On the other hand, for the BF/PCL-C fully-green composites fabricated by press molding, the mechanical properties increased with an increase in fiber mass fraction. The results of the biodegradability test showed the addition of BF could promote the biodegradation of composites in comparison with neat resin. The biodegradation of the composites at higher fiber mass fraction proceeded more extensively than that at low mass fraction. Therefore, we conclude that BF could be effectively used as reinforcement along with PP and biodegradable resin in preparation of various composites.

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