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Evaluation of Mechanical Properties of Highly Filled Jute Fiber Reinforced Composites

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Abstract: This study aims for development of highly filled jute fiber reinforced composites that contains jute fiber over fiber weight fraction 60%, and jute fiber reinforced composite was fabricated by the hot-pressing method. The molding temperature was changed from 175 ℃ to 230 ℃, to investigate the effect of molding temperature on the mechanical properties of jute fiber reinforced composites. The effect of surface treatment of jute fiber on the mechanical properties of jute fiber reinforced composites was also investigated. As a result, the jute fiber reinforced composites using surface treated fiber has low porosity, and the jute fiber reinforced composite having low porosity has high flexural strength and modulus. The jute fiber reinforced composite using acetone treated fiber molded at 200 ℃ has the maximum flexural strength and modulus.

Key words: Natural fiber, biodegradable plastics, high fiber weight fraction, surface treatment, mechanical properties.

1. Introduction

Fiber reinforced plastics have been used in various fields, including aerospace and aviation industries, automobiles, railways, civil engineering and construction, household appliances and medical equipment, due to their high specific strength and specific stiffness. Although GFRP (glass fiber reinforced composite) has excellent thermal and mechanical properties; this makes it difficult to treat and dispose of properly when disposed of [1]. In recent years, environmentally friendly composite materials reinforced with natural fibers and biodegradable resins, which are decomposed into water and carbon dioxide by the action of micro-organisms in nature, have therefore become a promising alternative to conventional fiber reinforced composites [2-9].

Jute fiber is obtained from *Corchorus capsularis*, and has long been widely used as jute rope, twine, bags, and hessian cloth, and because of its flexibility, is suitable for molding where a great deal of deformation is required. Jute fiber is also a fast-growing crop, with a harvest period of 100 days, and has some interesting characteristics such as low cost, low density, renewable, available in stable supply and reasonably good mechanical properties. Therefore, jute fiber is one of the most promising natural fibers as a reinforcing material for composite materials, and many composite materials have been developed using jute fibers [10, 11]. George et al. [12] concluded that PP (polypropylene)/jute yarn commingled composites have good stiffness and load bearing capability. Dobah et al. [13] studied the mechanics of novel woven JFRP (jute fibers reinforced polyester) laminates under uniaxial and multi-axial static and fatigue loading cases and found that the fatigue limit of JFRP (> 1 million cycles) is achieved at a stress level of 65% of the ultimate displacement. Arao et al. [14] developed a long jute fiber pellet to obtain a high aspect ratio of residual fiber after injection molding and clarified that the use of a well-compounded pellet in injection molding can significantly improve the Young's modulus and the tensile strength of jute fiber reinforced composites. Thermoplastic resins such

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as polypropylene and polylactic acid are often used as the matrix for jute fiber reinforced composites, where the composites are molded at a temperature higher than the melting point to improve the flowability of the resin and to impregnate the resin in the fiber bundles. In general, lignocellulosic fibers, which are composed of hemicellulose, cellulose, and lignin, are subjected to a reduction in tensile strength under thermal loading [15], and it is very important to clarify the relationship between molding temperature and mechanical properties of fiber reinforced thermoplastics using jute fibers, one of the lignocellulosic fibers. Furthermore, the main disadvantages of lignocellulosic fibers are the low compatibility and low interfacial adhesion with polymeric matrices [16]. Low fiber/matrix interfacial adhesion results in reduced stress transfer under load and low mechanical strength. Jute fibers are impregnated with mineral oil to provide flexibility and facilitate the spinning process [17]. Therefore, to improve the mechanical strength of jute fiber reinforced composites, surface cleaning must be optimized to remove oil from the jute fibers. If optimum molding temperatures and efficient surface cleaning were discovered, resulting in jute fiber reinforced composites with light weight and high mechanical properties, it would broaden the use of jute fibers in industrial applications.

The main objective of this study is to develop highly filled jute fiber reinforced composites that contain jute fiber over fiber weight fraction 60%. To realize this objective, the effects of molding temperature and surface treatment on the mechanical properties of jute fiber reinforced composites were also investigated.

2. Experimental Procedure

2.1 Materials

PLA (polylactic acid) resin (LANDY PL-1000, Miyoshi Oil & Fat Co., Ltd., Japan), which is emulsion type biodegradable resin, was used as matrix. Spread jute fiber bundle was obtained by spreading twisted jute yarn taken from plain woven jute fabric purchased from The Nihon Seima Co., Ltd., Japan. The length of the spread jute fiber bundles used as reinforcement is 3 mm.

2.2 Surface Treatment of Jute Fiber

In this study, the surface treatment of jute fibers was carried out using acetone and NaOH (sodium hydroxide) solutions of different concentrations.

For the acetone treatment, the spread jute fiber bundles were soaked in acetone and washed in an ultrasonic cleaner (AUC-06L, As One Co. Ltd., Japan) for 1 h. The spread jute fiber bundles were then removed from the acetone, washed with pure water, and dried in a constant temperature test chamber (EPN-115 Soyokaze, Isuzu Seisakusho Co., Ltd., Japan) at 60 ℃ for 20 h.

For the NaOH solution treatment, spread jute fiber bundles were soaked in a NaOH solution and kept at 30 ℃ for 2 h in a constant temperature test chamber. The spread jute fiber bundles were then removed from the NaOH solution, washed with pure water, and dried in a constant temperature test chamber at 60 ℃ for 20 h. The concentrations of the NaOH solutions were set at 0.5 mol/L and 1.0 mol/L.

2.3 Preparation of Preform

To facilitate the molding of green composites with a hot-pressing machine, the preforms were obtained by spreading the jute fibers evenly in a mold with internal dimensions of 90 mm × 90 mm, then pouring the PLA emulsion over it and impregnating the spread jute fibers shown in Fig. 1. The preforms were further dried at 80 ℃ for 24 h using a constant temperature test chamber (EPN-115 Soyokaze, Isuzu Seisakusho Co., Ltd., Japan). The fiber weight fraction of the jute fiber reinforced composites was 60%.

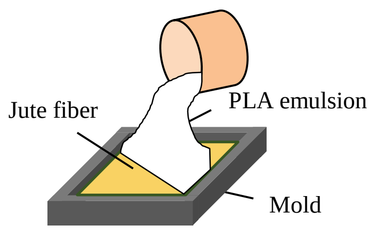


Fig. 1 Schematic of preform molding.

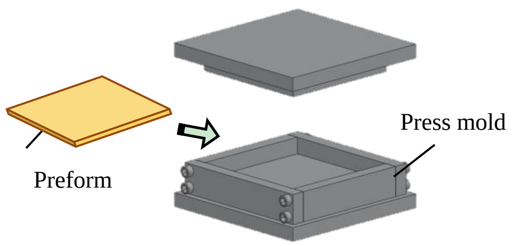


Fig. 2 Schematic of highly filled jute fiber reinforced composites molding.

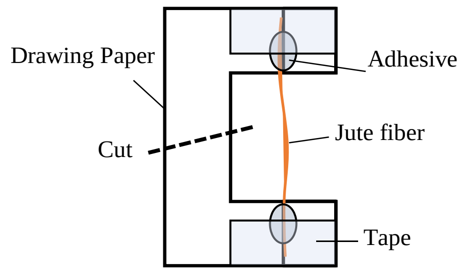


Fig. 3 Specimen of jute fiber tensile test.

2.4 Preparation of Highly Filled Jute Fiber Reinforced Composites

The fabrication of jute fiber reinforced composites was carried out using a hot-pressing machine (AH-2003, As One Co. Ltd., Japan) after setting the preform in the aluminum mold shown in Fig. 2. With respect to the process in hot press molding, temperature has dominant effect on the quality of jute fiber-reinforced composites. To investigate the effect of the thermal history of jute fiber reinforced composites during molding, five controlled temperature conditions were set at 175 ℃, 190 ℃, 200 ℃, 210 ℃ and 230 ℃. Moreover, the molding pressure and time were set at 20 MPa and 10 min, respectively.

2.5 Tensile Test of Jute Fiber

To investigate the effect of the thermal history and surface treatment of jute fiber, tensile tests were carried out using a universal testing machine (Ez-graph, Shimadzu Co. Ltd., Japan) at room temperature. The tensile test specimen of jute fiber is shown in Fig. 3. The gage length of the specimen is 20 mm. The tensile test was performed at the crosshead speed of 1.0 mm/min. The number of tensile tests for each condition was twenty.

2.6 Flexural Test of Highly Filled Jute Fiber Reinforced Composites

To evaluate the mechanical properties of the highly filled jute fiber reinforced composites, the 3-point flexural test was carried out using a universal testing machine (Ez-graph, Shimadzu Co. Ltd., Japan) at room temperature. A flexural test specimen was cut from the composites using a hand saw. The specimen dimensions were 15 mm × 60 mm × 2 mm. The flexural test was performed under the follow conditions: crosshead speed of 1.0 mm/min and span length of 40 mm. The number of flexural tests for each condition was five. The flexural strength σ_f and flexural modulus E_f were calculated from the following equations.

$$\sigma_f = \frac{3Pl}{2bh^2} \tag{1}$$

$$E_f = \frac{\Delta P l^3}{4bh^3\delta} \tag{2}$$

where P is the maximum load, b is the width of the specimen, h is the thickness of the specimen, l is the span length, δ is the deflection of the specimen, ΔP is the change in the load.

3. Results and Discussion

3.1 Surface of Jute Fiber

Figs. 4a-4d show optical microscope images of untreated jute fibers, jute fibers treated with acetone and jute fibers treated with NaOH solution. Impurities such as mineral oil adhered during the fiber production stage can be seen on the untreated jute fiber surface, whereas these impurities are not visible on the surface of jute fiber treated with acetone. However, impurities remain on the surface of jute fiber treated with NaOH solution compared to that of the acetone, indicating that the removal of impurities is not sufficient.

Figs. 5a-5d show SEM (scanning electron microscopy) micrographs of untreated jute fibers, jute fibers treated with acetone and jute fibers treated with NaOH solution.

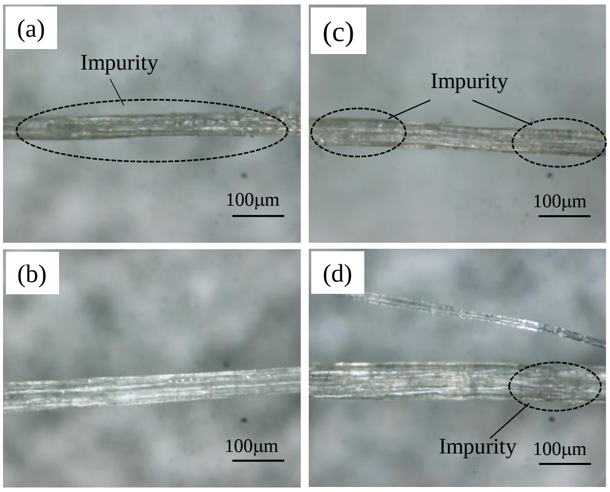


Fig. 4 Optical microscope images of surface of jute fiber, (a) untreated, (b) acetone, (c) NaOH 0.5 mol/L, (d) NaOH 1.0 mol/L.

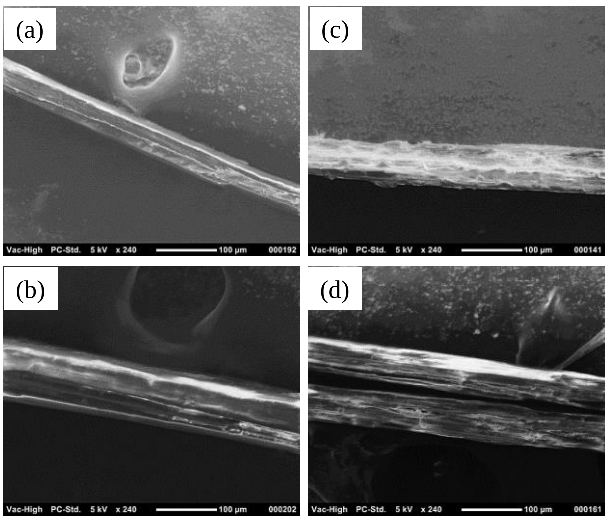


Fig. 5 SEM images of surface of jute fiber, (a) untreated, (b) acetone, (c) NaOH 0.5 mol/L, (d) NaOH 1.0 mol/L.

The surface of the untreated and the acetone treated jute fibers is smooth, whereas the surface of the NaOH treated jute fibers is rough. Moreover, the jute fiber surface treated with 1.0 mol/L NaOH solution can be seen to have fine fibers on the surface in comparison to those treated with 0.5 mol/L NaOH solution. Jute fiber has a structure in which bundles of fine fibers of cellulose and other materials are covered by integument of lignin and other materials, as shown in Fig. 6. Therefore, the appearance of fine fibers on the jute fiber surface is attributed to the removal of lignin, the main component of the integument, by NaOH treatment.

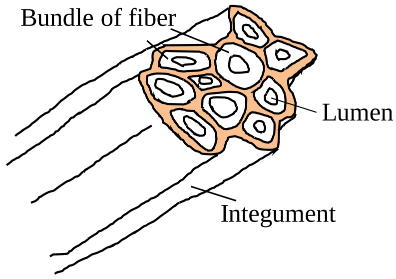


Fig. 6 Structure of jute fiber.

3.2 Tensile Properties of Jute Fiber

The relationship between tensile strength and Young's modulus of jute fibers and heating temperature is shown in Figs. 7a-7d. For untreated and acetone treated jute fibers, tensile strength and Young's modulus decrease with increasing heating temperature and tensile strength and Young's modulus decrease rapidly at heating temperatures above 200 ℃. These reductions are thought to be caused by the progressive degradation of cellulose and hemicellulose in jute fibers due to heating. Focusing on the unheated jute fibers, the tensile strength and Young's modulus of the NaOH treated jute fibers are higher than those of the untreated and acetone treated fibers.

The tensile strength and Young's modulus of NaOH treated jute fibers increase between heating temperatures of 175 ℃ and 190 ℃ and decrease significantly above heating temperature of 190 ℃. The higher tensile strength and Young's modulus of NaOH treated jute fibers can be attributed to denaturation of the jute fibers, such as mercerization. Mercerization is a process in which cellulosic fibers, such as cotton, are treated with alkali to change their properties. Mercerization of natural fibers is known to improve tensile strength by changing the crystalline structure of the cellulose [18]. However, NaOH treated jute fibers show a decrease in tensile strength and Young's modulus in the lower temperature range compared to untreated and acetone treated fibers. Generally, the pyrolysis of cellulose in jute fibers starts at around 200 ℃, whereas the pyrolysis of lignin starts at about 350 ℃ [15]. The removal of lignin through NaOH treatment may have

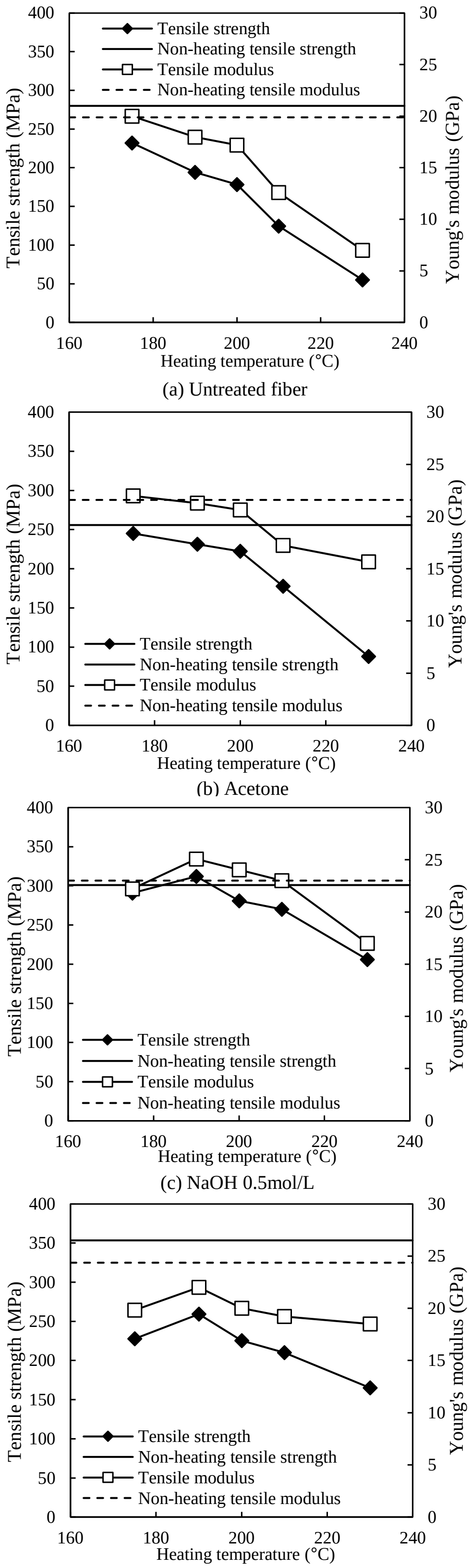


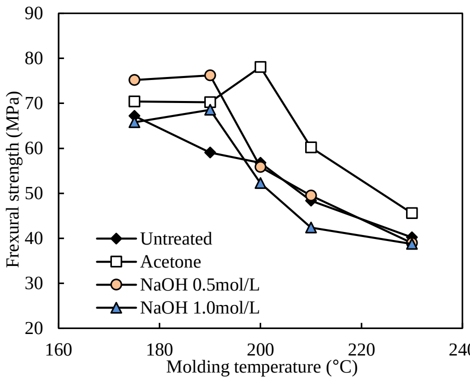
Fig. 7 Relationship between tensile strength and Young's modulus of jute fiber and heating temperature.

led to the exposure of cellulose at the fiber surface, reducing tensile strength and modulus at lower temperatures. Jute fibers treated with NaOH at 1.0 mol/L have more lignin removed than those treated with 0.5 mol/L, resulting in lower tensile strength and Young's modulus on heating. It can be concluded that the removal of lignin leads to a reduction in heat resistance.

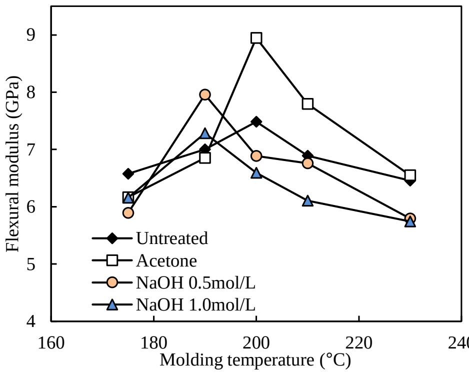
3.3 Flexural Properties of Highly Filled jute Fiber Reinforced Composite

The relationship between flexural strength and modulus of highly filled jute fiber reinforced composites and heating temperature is shown in Figs. 8a-8b. In the case of acetone treated jute reinforced composites, both flexural strength and modulus of the composites increase between molding temperatures of 175 ℃ and 200 ℃, whereas they decrease rapidly above the molding temperature of 200 ℃. Fig. 9 shows the flexural stress-displacement curves for jute fiber reinforced composites at a molding temperature of 200 ℃. The behavior of the stress-displacement curve of the acetone treated jute fiber reinforced composites shows a linear behavior from initiation to failure with a higher slope of the stress-displacement curve compared to the other treatment conditions. The relationship between porosity and molding temperature of jute fiber reinforced composites is shown in Fig. 10.

Under all surface treatment conditions, the porosity of jute reinforced composites decreases with increasing molding temperature up to 200 ℃ and increases above 200 ℃. The porosity of composites treated with acetone and NaOH is reduced in comparison to untreated composites. This indicates that the removal of impurities from the fiber surface facilitates the impregnation of the resin into the fibers. The reduction in porosity of the jute fiber reinforced composites can be attributed to the higher fluidity of the PLA resin due to the higher molding temperatures, resulting in increased flexural strength and flexural modulus of the composites. On the other hand, the increase in porosity



(a) Flexural strength



(b) Flexural modulus

Fig. 8 Relationship between flexural strength and modulus of highly filled jute fiber reinforced composites and heating temperature.

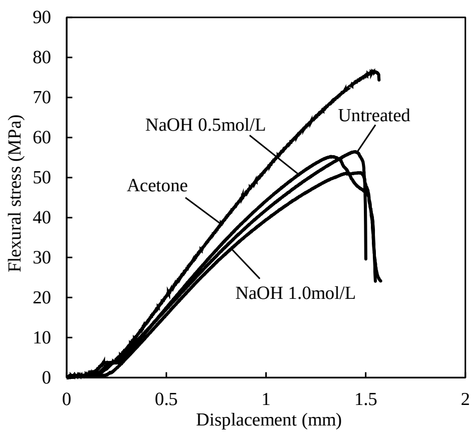


Fig. 9 Flexural stress-displacement curve of highly filled jute fiber reinforced composites.

of the composites at molding temperatures above 200 ℃ is believed to be due to the increased fluidity of the PLA resin as the molding temperature increases, resulting in the resin flowing out of the mold. In addition, the carbon dioxide gas generated by the decomposed fibers in the mold increases the number of porosities in the composites. Therefore, the reduction

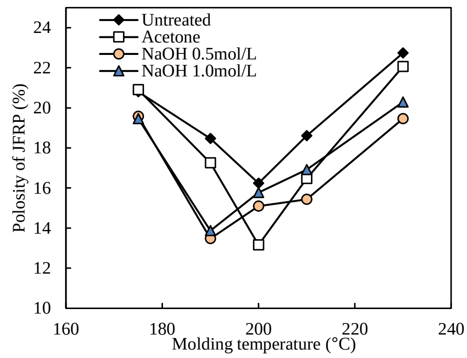


Fig. 10 Relationship between porosity and molding temperature of jute fiber reinforced composites.

in the flexural strength and flexural modulus of the composites above the molding temperature of 200 ℃ can be attributed to increased porosity in the composites and thermal degradation of the jute fibers.

3.4 Fracture Morphology of Highly Filled Jute Fiber Reinforced Composites

The fracture surface of the jute fiber reinforced composites specimen after the flexural test is shown in Fig. 11. The fracture surfaces of the untreated and NaOH treated composites specimens show pull-out of the jute fibers, whereas the acetone treated specimens do not show any such pull-out of the fibers. As mentioned in the previous section, impurities such as mineral oil adhered to the untreated jute fibers and these impurities were not removed from the NaOH treated jute fibers, which is believed to have weakened the interfacial adhesion between the fibers and the resin and reduced the flexural strength and modulus of the jute fiber reinforced composites. It is believed that the flexural strength and modulus of the jute fiber reinforced composites can be improved if the impurities adhering to the jute fibers are sufficiently removed, as is the case with the acetone treatment. As indicated in the previous section, although the NaOH treatment increased the strength and modulus of the jute fibers, it did not sufficiently remove the impurities from the jute fibers, resulting in a decrease in the strength and modulus of the jute fiber reinforced composites. Therefore, it is believed that the strength and modulus of jute fiber reinforced composites can be improved by

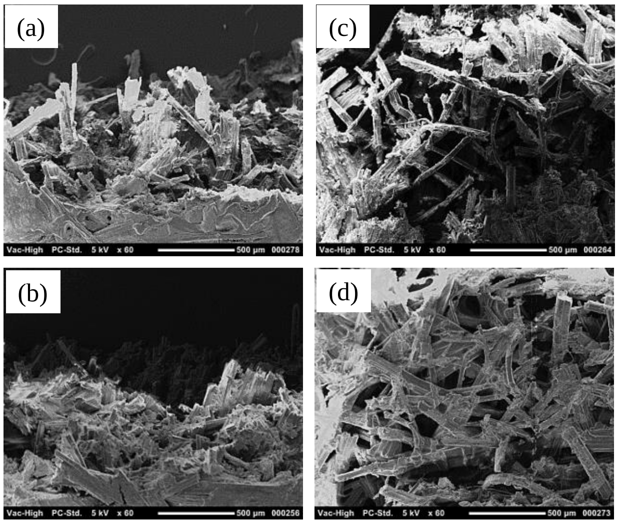


Fig. 11 SEM images of fracture surface of highly filled jute fiber reinforced composites, (a) untreated, (b) acetone, (c) NaOH 0.5 mol/L, (d) NaOH 1.0 mol/L.

improving the NaOH treatment process to sufficiently remove impurities adhering to jute fibers.

4. Conclusions

In this study, randomly oriented jute fibre reinforced composites with jute fibers as reinforcement and PLA as matrix were molded to develop highly filled biodegradable composites and the effects of molding temperature and surface treatment on their mechanical properties were investigated. Some conclusions could be obtained as follows.

(1) Up to the molding temperature of 200 ℃, the increase in molding temperature increases the fluidity of the PLA resin and reduces the porosity in the jute fiber reinforced composites. This increases the flexural strength and flexural modulus.

(2) At molding temperature above 200 ℃, the flexural strength and flexural modulus of jute fiber reinforced composites decrease due to increased porosity in the composites and thermal degradation of the jute fibers.

(3) The acetone treatment removes impurities from the jute fibers, which increases the flexural strength and modulus of the jute fiber reinforced composites.

(4) NaOH treatment increases the tensile strength and tensile modulus of jute fibers. However, it reduces the heat resistance.

(5) NaOH treatment reduces the flexural strength and flexural modulus of jute fiber reinforced composites. This is because the impurities adhering to the jute fibers have not been removed.

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