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Thermal conductivity of PLA-bamboo fiber composites

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Abstract—'Green' composites were fabricated from poly lactic acid (PLA) and bamboo fibers by using a conventional hot pressing method. The insulating properties of the PLA-bamboo fiber 'green' composites were evaluated by determination of the thermal conductivity, which was measured using a hot-wire method. The thermal conductivity values were compared with theoretical estimations. It was demonstrated that thermal conductivity of PLA-bamboo fiber 'green' composites is smaller than that of conventional composites, such as glass fiber reinforced plastics (GFRPs) and carbon fiber reinforced plastics (CFRPs). The thermal conductivity of PLA-bamboo fiber 'green' composites was significantly influenced by their density, and was in fair agreement with theoretical predictions based on Russell's model. The PLA-bamboo fiber composites have low thermal conductivity comparable with that of woods.

Keywords: Bamboo fiber; poly lactic acid; thermal conductivity; density; Russell's model.

1. INTRODUCTION

In recent years, 'green' composites, which are fabricated from a plant-derived resin and natural fibers, have received a lot of public attention as one of the environment-friendly composite materials [1–9]. Many comprehensive research projects on the mechanical properties of the 'green' composites have been carried out, whereas only a little research on their functionality has been carried out [10]. The natural fiber used as a reinforcement of the 'green' composites usually has a hollow structure [7], and therefore it is expected to provide excellent properties, which cannot be achieved using conventional solid fibers such as glass fibers and carbon fibers. It is

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suggested from this unique structure that natural fiber reinforced composites should have good insulation properties, which is one of the most important functionalities using such materials.

Heat insulating materials, which are made from glass wool or rock wool, are widely used in various fields from general housing to nuclear reactors. A wide variety of effects such as the reduction of energy cost and the improvement in manufacturing efficiency are expected by the appropriate use of the heat insulating materials. However, glass fibers, which are representative of mineral fibers, are mainly used in the heat insulating material as a reinforcing phase. The glass fiber reinforced insulating materials meet many difficulties in thermal recycling after use, and therefore they have relatively high environmental load, because it is reported that the glass fibers often react with ceramic furnace materials used in a waste incinerator, and that this reaction will shorten the service life of the waste incinerator.

Although a large number of researches have been carried out on natural fiber reinforced composites, little is known about their thermal conductivity. Mangal *et al.* examined the thermal conductivity of pineapple leaf reinforced phenol formaldehyde composites (fiber content was 40 wt%) [11]. They also investigated the effect of chemical surface treatment on their thermal properties, and compared with the values calculated from Bruggman's model. Another attempt was made by Khedari *et al.* [12]. They fabricated insulating particleboards from durian peels and coconut coir fibers, and examined their mechanical properties and the relationship between thermal conductivity and board density. They concluded that the thermal conductivity (durian and coconut coir fiber boards) was fairly low varying between 0.054 and 0.185 and that the boards had low strength compared with wood because of the difference in the internal microstructures. However, the measured density range was limited to the range from 0.3 to 0.9 g/cm^3. Recently, Kim *et al.* have examined the thermal conductivity of polypropylene-based thermoplastics reinforced by 50 wt% of chopped natural fibers, e.g. kenaf, hemp, flax and sisal fibers [13]. They reported that the thermal conductivity increased by adding coupling agents, such as maleated polypropylene and silane. However, there was no discussion on the effect of sample density on thermal conductivity.

In the meantime, the 'green' composite insulating materials handled in this study are able to be thermally recycled in the waste incinerator, and their environmental load seems to be small compared with conventional glass fiber reinforced insulating materials, since carbon dioxide, one of the typical global warming gasses, emitted during the incineration of 'green' composites, has a characteristic of being carbon-neutral [14].

Using a poly(lactic acid) (PLA), which is one of the representative plant derived biodegradable resins, as a matrix material, bamboo fiber reinforced 'green' composites (abbreviated as BFGC hereafter) were produced experimentally in this study. Thermal conductivity, which is one of the representative indexes of insulation property of materials, was evaluated both experimentally and theoretically, and the thermal conductivity of BFGC was compared with that of woods. The purpose of this study is to investigate the insulation properties of BFGC as a function of sample's density.

2. EXPERIMENTAL

2.1. Raw materials

Bamboo (*Phyllostachys pubescens*) grown in Anan City, Tokushima Prefecture, Japan, was used as raw material. Bamboo fibers were extracted by using a steam explosion method [9, 15]. Before carrying out the steam explosion treatment, the bamboo stem was heated in the steam at 180°C and 0.98 MPa for 40 min, and this steam explosion process was repeated three times. Bamboo fiber bundles were extracted from the stream exploded bamboo stem. No surface treatment of bamboo fiber was carried out. The photograph of bamboo fiber bundles extracted by the steam explosion method is shown in Fig. 1.

A PLA-based, water-dispersion type biodegradable resin (Miyoshi Oil and Fat Co. Ltd., PL-1000) was used as a matrix material. This aqueous resin contains spherical particles with an average diameter around 5 μm, and the solid fraction of this resin is approximately 40% by weight.

2.2. Molding method of BFGC

First, the flocculent bamboo fiber was prepared from steam exploded bamboo fiber bundle by using a home-use mixer (Fig. 2). Next, soft cells and other flecks of dusts were washed out with running water. The washed flocculent bamboo fiber was then dried at 70°C for 15 h using a circulation type oven (Toyo Seisakusho Kaisha, Ltd., DRX-420DA). Preforms with a fiber content of 60% by weight were

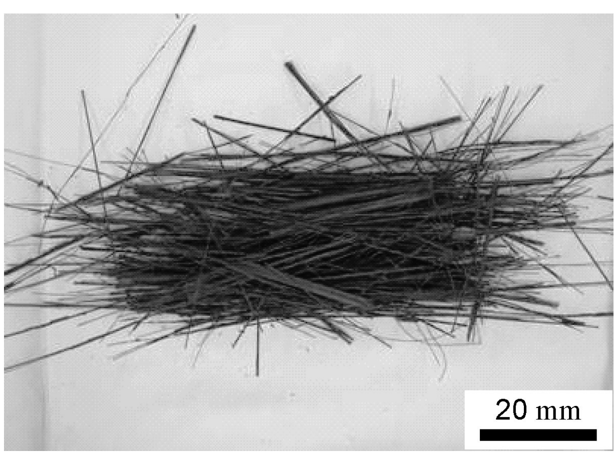

Figure 1. Photograph of bamboo fiber bundle extracted by steam explosion method.

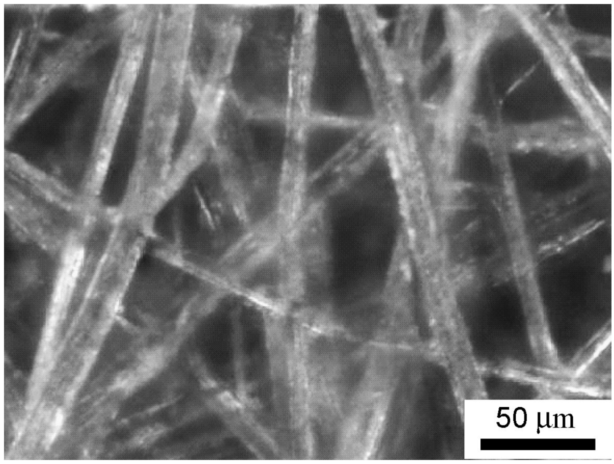

Figure 2. Photograph of flocculent bamboo fiber.

prepared by mixing of bamboo fiber and PLA resin, followed by drying at 70°C for 15 h using the same oven. Finally, several sheets of performs were hot pressed by using a hot pressing machine (Imoto Machinery Co. Ltd., IMC-16EF) equipped with two platens 160 mm square. The hot pressing was performed at 180°C for 10 min. The average fiber length in BFGC sample was approximately 1.50 mm. The BFGC samples with a wide range of densities were fabricated by altering the molding pressure. For example, the composites with sample densities of 0.26, 0.72 and 1.24 g/cm^3 are obtained by hot pressing at 1.6, 15 and 45 MPa, respectively.

2.3. Thermal conductivity measurement

The thermal conductivity of BFGC sample with bamboo fiber content of 60% by weight was measured using a quick thermal conductivity meter (Showa Denko Co., Shotherm QTM-DII) that is operated on the basis of a hot wire method. This hot wire method is a transient dynamic technique, and commonly used to measure the thermal conductivity of insulating bricks and plastic materials of relatively low thermal conductivity. A special probe which contains a wire heater and a thermocouple was placed on the specimen surface with a constant load. When constant heat energy is given to the heater, the temperature of the heat wire, which is detected by the embedded thermocouple, rises exponentially. The thermal conductivity can be calculated directly from this temperature rise in a known time interval. Therefore, the required measurement time for this method is short; specifically it is less than one minute. Before measurement, the quick thermal conductivity meter was always calibrated using three kinds of reference materials with known value of thermal conductivity. The size of the BFGC sample was 100 × 100 × 10 mm. Thermal conductivity data was measured at least 5 times and the accuracy of the hot wire method was within the error of 3.0%.

3. RESULTS AND DISCUSSION

The thermal conductivity of BFGC with 60 wt% fiber is shown in Fig. 3. The thermal conductivity data for density of zero corresponds to that of the air (0.026 W/(m · K)). The thermal conductivity of BFGC gradually increases as the density of the material increases. In other words, the thermal conductivity of BFGC highly depends on its density as is the case for conventional heat insulating materials such as glass wool and rock wool. A theoretically estimated thermal conductivity for two-phase composite material containing void, λ^*, is expressed as follows (Russell's model [16]):

$$\lambda^* = \left\{ \frac{1 - V^{1/3}}{\lambda_s} + \frac{V^{1/3}}{(1 - V^{2/3})\lambda_s + V^{2/3}\lambda_g} \right\}^{-1}, \tag{1}$$

where V is the porosity (i.e. void content) of the BFGC sample, λ_s is the thermal conductivity of solid phase, and λ_g is the thermal conductivity of gas phase (the air in this case; $\lambda_g = 0.026$ W/(m · K)).

Figure 4 illustrates the thermal conductivity of BFGC as a function of sample's porosity. The porosity, V was calculated by the following equation:

$$V = \frac{\rho_c - \rho_a}{\rho_c}, \tag{2}$$

where ρ_a is a sample density, and ρ_c is a theoretical density of BFGC with 60 wt% fiber (1.344 g/cm^3). In this graph, the dotted line represents the theoretical thermal conductivity of BFGC calculated from equation (1) showing a reasonable agreement with experimental data. The fitted value of the thermal conductivity of the solid phase, λ_s, is 0.340 W/(m · K), and this value is greater than that of PLA (0.20 W/(m · K)) and therefore the thermal conductivity of bamboo fiber will be greater than 0.340 W/(m · K).

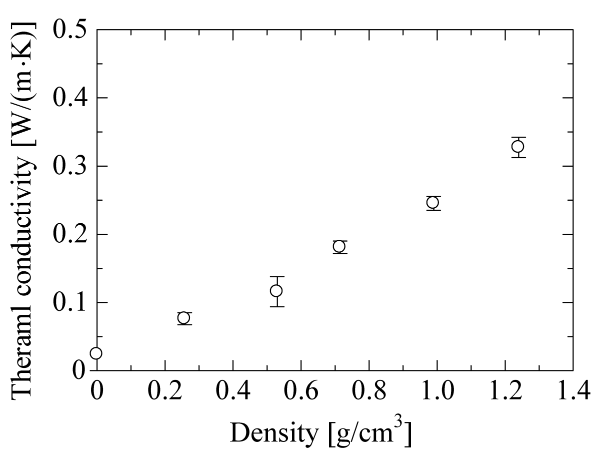

Figure 3. Variation of thermal conductivity of BFGC with density.

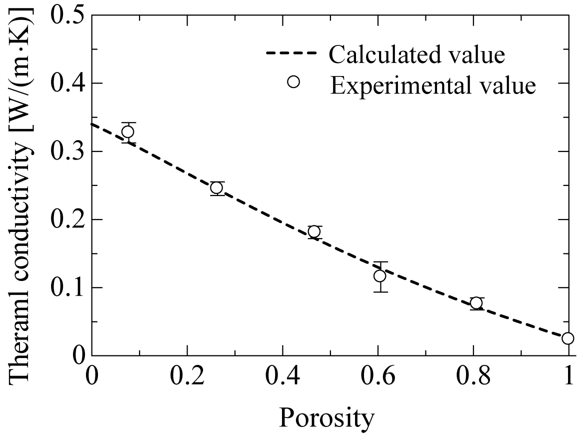

Figure 4. Measured thermal conductivity of BFGC and calculated values from equation (1).

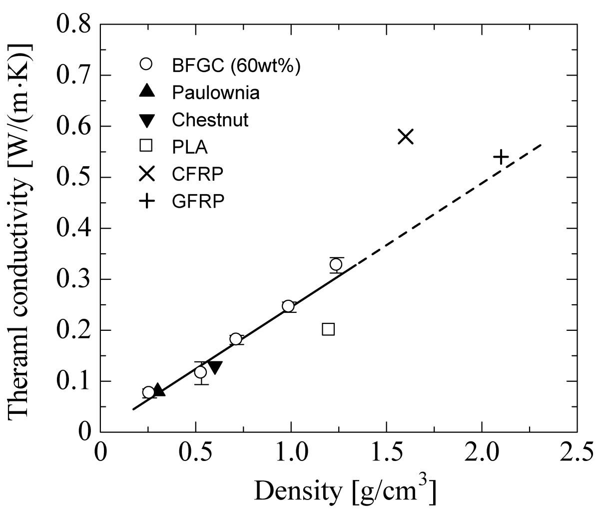

Figure 5. Comparison of thermal conductivities between BFGC and other materials.

The relationship between thermal conductivity and density of various materials is shown in Fig. 5. The value of thermal conductivity of BFGC becomes about a half in comparison with those of glass fiber reinforced plastics (GFRPs) and carbon fiber reinforced plastics (CFRPs), and it can be seen that BFGC has good adiabatic properties. As a reason for such a small thermal conductivity of BFGC, it should be noted that the density of BFGC is smaller that those of GFRP and CFRP. The thermal conductivity data of CFRP is located in the upper part of the prediction line indicated by dotted line in Fig. 5, and it is proven that BFGC has better adiabatic properties compared with CFRP even taking into account of the density difference.

The reason why BFGC has low thermal conductivity would be that cellulose, which is the major component of natural fiber, has much lower thermal conductivity compared with carbon fiber, and that natural fiber has a hollow structure, i.e. lumen. It is seen that the thermal conductivity data for a couple of woods such as paulownia and chestnut are located on the straight line in Fig. 5. It appears that BFGC has comparable thermal properties to woods.

4. CONCLUSIONS

'Green' composite thermal insulating board was fabricated from a plant derived resin and bamboo fibers. The thermal conductivity of this thermal insulating board was measured experimentally, and then the insulation properties were examined from a theoretical viewpoint. Results obtained are briefly summarized as follows:

1. The thermal conductivity of BFGCs depends on their density, and the thermal conductivity increases with increasing density as indicated in other conventional materials.
2. The thermal conductivity of BFGC is smaller than that of GFRP and CFRP. This low thermal conductivity of BFGC is derived from its low density.
3. The thermal conductivity of BFGC is approximately equal to that of woods, as compared with the same density level.

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