Thermal characteristics of PLA-bamboo composites

K. Kusano[1], H. Takagi[1], S. Kako[2], Y. Gennai[2] & A. Ousaka[1]
[1]*Institute of Technology and Science, The University of Tokushima, Japan*
[2]*Graduate School of Engineering, The University of Tokushima, Japan*

Abstract

The effective properties for the thermal characteristics of polylactic acid (PLA) bamboo composites, such as thermal conductivity, density and porosity were investigated experimentally. The thermal insulation characteristics are significantly dominated by these parameters. The thermal conductivity was measured by the transient hot wire method and the steady state method. The measured data was compared with each other and also used for the verification of the validity of Russell's theoretical thermal conductivity model for green composites. The results show that the thermal conductivity of PLA-bamboo depends on the direction of fiber alignment as well as the direction of stacking. The thermal conductivity decreases gradually with decreasing the porosity (i.e., increasing the density of fiber). It was also clear that the theoretical estimation based on Russell's model is adaptable to the anisotropic PLA-bamboo composites. All of the thermal conductivity measured by using the steady state method is lower than that measured by using the hot wire method. The thermal conductivity through the thickness direction is lower than that of surface plane averaged thermal conductivity. Due to the anisotropicy of its low thermal conductivity, the PLA-bamboo "green" composites have excellent insulation properties.
Keywords: bamboo fiber, polylactic acid, thermal conductivity, transient hot wire method, steady state method, porosity, Russell's model, thermal insulation characteristics.

WIT Transactions on The Built Environment, Vol 97, © 2008 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/HPSM080191

1 Introduction

The global environmental and energy problems have received much attention during recent decades. As one of the solutions to such problems, composites made from a plant-derived resin and natural fibers, known as "green" composites, have come to attention as one of the alternative plastic products. Due to its character of environmental impact, there are many researches about this sort of material. However, most of the studies were aimed at obtaining the mechanical properties of "green" composites [1–9], while there is very little research regarding the functionality [10, 11]. The natural fibers used as a reinforcement of the "green" composites have a hollow structure [7], which has not appeared clearly in conventional solid fibers such as glass fibers and carbon fibers. The hollow structured composites are expected to have insulation properties, i.e. of a heat insulation nature and sound/vibration insulation nature, etc. These functions are especially needed, for example, in the field of building and house materials.

The number of high heat insulated and airtight houses in Japan has increased gradually since the energy crisis of the 1970s. The temperature non-uniformity over the room/house is minimized and the energy for the air-conditioning and heating can be significantly reduced in such a house. The high heat insulated and airtight house is more energy saving and environmentally protective than the traditional house, however, its building costs are about 10% higher than that of the same size normal type of house because the high heat insulated and airtight house has to satisfy the next generation energy saving standards noted in Japan's rationalization in energy use law. These standards provide the maximum specific heat loss coefficient of the house Q, which indicates the overall performance of the heat insulation of the house (defined as the energy loses per hour from the inside of the house divided by the gross floor area when the temperature difference between the inside and the outside of the house is 1 °C, $W/(m^2 \cdot K)$), and the minimum thickness of the heat insulator (i.e., required thermal resistance) at the floor, ceiling and wall. Although these standards are not compulsory, but simply represent a numerical target, preferential interest rates and additional house loans can be applicable to a heat isolating construction that clears the above standards. In the house, glass wool or rock wool is usually used as a heat insulator inside the walls and ceiling because of its availability and price. Glass wool is useful and easy to recycle, but the thickness of the insulator will need to be increased if the temperature difference between the inside and the outside of the house is to fall within acceptable parameters. In the meantime, for temperature uniformity within the room, the floor, wall and ceiling need to have a relatively high thermal conductivity. In other words, both heat insulation in the through-thickness direction and a thermally well-conducting nature over the plane direction are required. For the purpose of insulating/conducting, "green" composites seem to satisfy this requirement. In addition, "green" composites seem to be useful not only in the fields of building and houses, but also in the fields of housing the electric devices.

www.witpress.com, ISSN 1743-3509 (on-line)

The authors have formerly produced bamboo fiber (as a matrix material) reinforced “green” composites (BFGC) by using polylactic acid (PLA), which is one of the representative plant derived biodegradable resins, and investigated the thermal conductivity of BFGC by the hot wire method [11]. Bamboo grows more quickly than other woods, so it will be available throughout the year and is inexpensive. Bamboo fibers are elastic and have such high thermal and electric conductivity that Thomas Edison used them to make filaments for his light bulbs. Thermal conductivity is one of the important properties of thermal characteristics of materials, such as the property of insulation. The aims of this study are to investigate the anisotropic thermal characteristics of the BFGC by using another measurement method for thermal conductivity and comparing existing data, and to verify the validity of theoretical estimation based on Russell’s model [12].

2 Experimental apparatus and methods

2.1 Test material

Bamboo fibers were extracted by using the steam explosion method [9, 13]. Before carrying out the steam explosion treatment, the bamboo stem was heated at 180 °C and 0.98 MPa for 40 minutes. This steam explosion process was repeated three times. Bamboo fiber bundles were extracted from the steam exploded bamboo stem. No surface treatment of the bamboo fiber was carried out.

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

2.2 Molding method of BFGC

The flocculent bamboo fiber was prepared from the steam exploded bamboo fiber bundle by using a conventional household mixer at first. Next, soft cells and other flecks of dust were washed out with running water. The washed flocculent bamboo fiber was then dried at 70 °C for 15 hours using a circulation type oven (Toyo Seisakusyo Kaisya, Ltd., DRX-420DX). Preforms with a fiber content of 60% by weight were prepared by mixing bamboo fiber and PLA resin, followed by drying at 70 °C for 15 hours using the same oven. Finally, several sheets of preforms were hot pressed by using a hot pressing machine (Imoto Machinery Co. Ltd., IMC-16EF) equipped with two platens of 160 mm square. The hot pressing was performed at 180 °C for 10 minutes. The BFGC samples with a wide range of densities were fabricated by changing the molding pressure [14].

2.3 Thermal conductivity measurements

The thermal conductivity of the BFGC samples with various bamboo contents were measured by two measurement methods. Before the measurement, all the instruments were adjusted correctly and calibrated using three kinds of reference materials with well-known values of thermal conductivity. In the following section, we introduce two measurement methods.

2.3.1 Hot wire method

The hot wire method can measure the averaged thermal conductivity of specimen over the plane direction. A quick thermal conductivity meter (Showa Denko Co., Shotherm QTM-DII) was used for this method. In this method, the measured thermal conductivity is an apparent thermal conductivity averaged over the surface plane, which contacts the hot wire. While only obtaining the average thermal conductivity, this method is frequently used because of the easiness of operation and measurement speed.

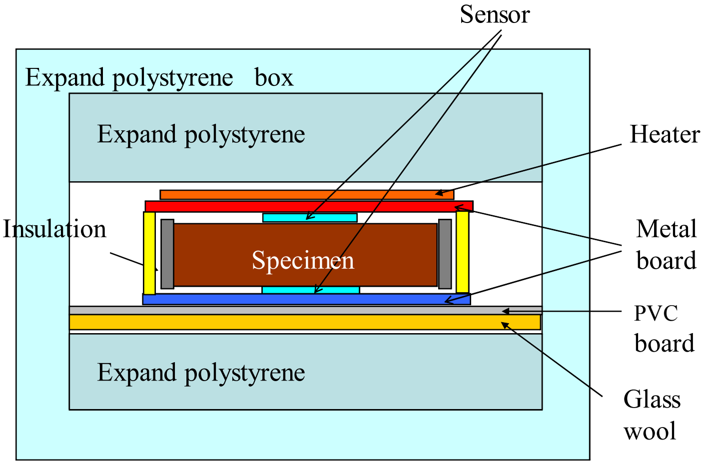

Figure 1: Schematic diagram of the steady state method.

2.3.2 Steady state method

The steady state method measures thermal conductivity through the thickness direction. In the present study, the measurement procedure was determined by the flat plate comparison method according to JIS A 1412-1977 [14]. Fig. 1 shows the schematic diagram of the steady state method (flat plate comparison method). The experimental apparatus is composed of (1) hot flat plate, (2) cold flat plate, (3) temperature and heat flux sensor, (4) heat controller, (5) specimen and (6) heat insulators (glass wool and polystyrene). In the measurement process, the temperature and heat flux sensor was adhered to the specimen (100 mm × 100 mm × 9 mm) at first; both the specimen and the sensor were pressed by the hot and cold flat metal plates. The experimental apparatus was insulated from ambient temperature by heat insulators in order to minimize the heat loss from the specimen. The thermal conductivity λ is estimated from the temperature difference between the flat metal plates and the heat flux when steady state is reached. The estimated thermal conductivity is as follows:

$$\lambda = \frac{(q_H + q_C)}{2} \times \frac{D}{(T_H - T_C)} \qquad (1)$$

where q, T and D are measured heat flux [W/m^2], temperature [°C] and thickness of the specimen [m], respectively. Subscript "H" and "C" denote the hot flat plate side and cold plate side, respectively. Calibration was achieved by using a polytetrafluoroethylene plate (PTFE), a polyvinyl chloride plate (PVC) and an acrylic glass plate (polymethyl methacrylate, PMMA), which have well-known properties.

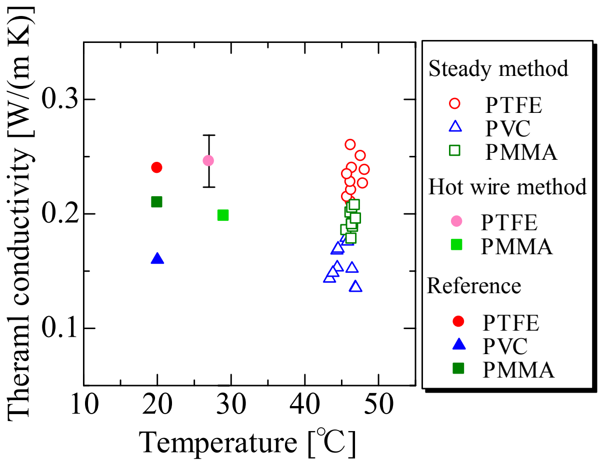

Figure 2: Verification of the measurement method.

3 Results and discussion

Before investigating the thermal characteristics of PLA-bamboo, the validity of the thermal conductivity measurement by using the steady state method was examined. Fig. 2 shows the thermal conductivities measured by two methods and well-known reference values [15]. Please note that PTFE, PVC and PMMA have the isotropic feature of thermal conductivity, so that these thermal conductivities are supposed to be independent from measurement methods. Therefore these materials were adopted as reference material. As for the polymer material, the thermal conductivity of a perfect crystallized polymer is slightly decreased with increasing the temperature, whereas that of a non-crystallized polymer is slightly increased with increasing the temperature. Since a partially crystallized polymer has intermediate features, the thermal conductivity is almost independent from the change in the temperature below the glass transition temperature. Generally speaking, the thermal conductivity of the polymer material is hardly affected by the temperature. Although each measurement temperature is different, if the effect of the temperature dependency on the thermal conductivity is negligible, the deviation between the reference value and the value measured by the steady

www.witpress.com, ISSN 1743-3509 (on-line)

state method is about 2–7%, the derivation between the value measured by two methods is 4–6%. Therefore, the reliability of the measurement is sufficiently high.

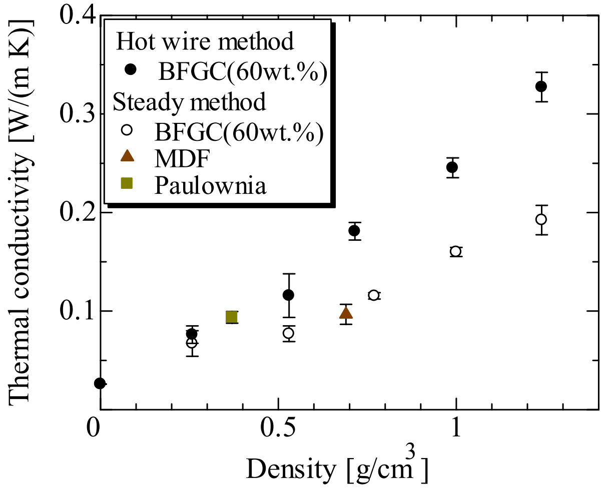

Figure 3: Relation between thermal conductivity and density and comparison of BFGC and other wood material.

In order to investigate the effect of the density on the thermal conductivity, the experiments were performed for changing the density of BFGC and other wood material (medium density fiberboard: MDF and Paulownia). Here, the BFGC sample with the fiber content is constant (60%). From fig. 3, it is clear that the measurement value by the steady state method is lower than that by the hot wire method. This is caused by the difference of the measurement principle between the two methods, as the steady state method measures through the thickness direction, while the hot wire method indicates surface plane averaged thermal conductivity. It is also shown in fig. 3 that the thermal conductivity of the BFGC is increased with increasing the density. This may be caused by the uneven distribution of the void. BFGC is made from several sheets by hot pressing, so that there is less air space on the pressed surface than that inside the body. The pressed surface has fewer voids than inside. The void of the BFGC is filled with air (fig. 4), which has very low thermal conductivity (0.026 W/(mK)) and is superior in insulation property to ordinary material, so that the volume of the void, that is porosity, dominates the thermal conductivity of BFGC. The thermal conductivity of BFGC is also lower than that of Paulownia, and is the same as that of MDF. The reason why BFGC has many void is because BFGC has a lot of cellulose, which is a major component of natural fiber.

Fig. 5 shows the relation between the porosity of BFGC and thermal conductivity. Porosity is estimated by using the theoretical density (1.34 g/m^3) and the apparent density of BFGC. As shown in fig. 3, the thermal conductivity

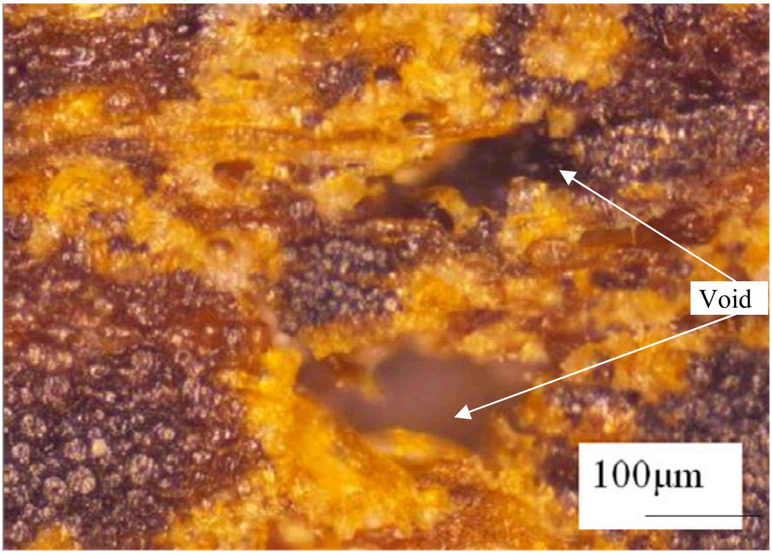

Figure 4: Photograph of BFGC.

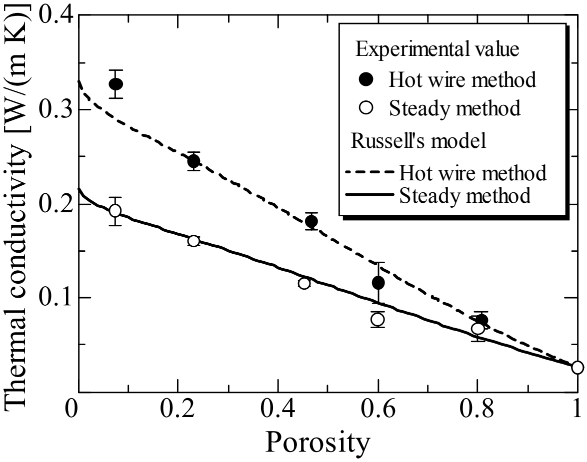

Figure 5: Effect of the porosity on the thermal conductivity.

of BFGC is increased with decreasing the porosity. This is the same reason why the volume of voids density of BFGC affects the thermal conductivity. The relationship between the porosity and the thermal conductivity is almost linear. In the present study, we applied the theoretical estimation based on Russell's model [15] for the thermal conductivity of BFGC. The thermal conductivity of the air including porous material, λ_p is defined as follows:

$$\lambda_p = \left\{ \frac{1-p^{1/3}}{\lambda_s} + \frac{p^{1/3}}{\left(1-p^{2/3}\right)\lambda_s + p^{2/3}\lambda_g} \right\}^{-1} \tag{2}$$

where λ_p, λ_s, λ_g and p are thermal conductivity of air including porous material, that of solid, that of gas and porosity, respectively. The measured value of the BFGC is coincident with the theoretical estimated value. Calculation by using the known and measured value of λ_p, λ_g and p gives the value of λ_s, which is 0.336 W/(mK) in the hot wire method and 0.216 W/(mK) in the steady state method. The difference between these values is affected by the direction of fiber alignment and the direction of the stacking of the film when BFGC is hot pressed. In the same layer, the thermal conductivity is relatively high (which is measured by the hot wire method), for the direction through the layers, which is lower than the former.

4 Conclusions

"Green" composite, BFGC was fabricated from a plant derived resin and bamboo fiber. The anisotropic thermal characteristics of the BFGC were investigated by using two measurement methods for thermal conductivity and validity of theoretical estimation based on Russell's model was verified. Based on the results obtained, our conclusion can be summarized as follows:

1) All of the thermal conductivity measured by using the steady state method is lower than that measured by using the hot wire method.
2) The thermal conductivity through the thickness direction is lower than that of surface plane averaged thermal conductivity.
3) The density of BFGC affects the thermal conductivity of BFGC. When the bamboo fiber content is constant, increasing the density causes the decreasing of the void in the BFGC.
4) The thermal conductivity of BFGC is increased linearly with increasing the porosity.

References

[1] Wollerdorfer, M. & Bader, H., Influence of natural fibres on the mechanical properties of biodegradable polymers. *Industrial Crops and Products*, **8(2)**, pp. 105–112, 1998.

[2] Luo, S. & Netravali, A. N., Interfacial and mechanical properties of environment-friendly "green" composites made from pineapple fibers and poly (hydroxybutyrate-co-valerate) resin. *Journal of Material Science*, **34**, pp. 3709–3719, 1999.

[3] Luo, S. & Netravali, A. N., Mechanical and thermal properties of environment-friendly "green" composites made from pineapple leaf fibers and poly (hydroxybutyrate-co-valerate) resin. *Polymer Composites*, **20**, pp. 367–378, 1999.

[4] Lodha, P. & Netravali, A. N., Characterization of interfacial and mechanical properties of "green" composites with soy protein isolate and ramie fiber. *Journal of Material Science*, **37**, pp. 3657–3665, 2002.

[5] Netravali, A. N. & Chabba, S., 'Composites get greener', invited review Article, *Materials Today*, pp. 22–29, April 2003.

[6] Mohanty, A. K., Misra, M. & Hinrichsen, G., Biofibers, Biodegradable polymers and biocomposites: An overview, *Macromolecular Materials and Engineering*, **276/277**, pp. 1–24, 2000.

[7] Mueller, D. H. & Krobjilowski, New Discovery in the properties of composites reinforced with natural fibers. *Journal of Industrial Textile*, **33**, pp. 110–130, 2003.

[8] Takagi, H, & Ochi, S., Characterization of high-strength "green" composites using Manila hemp fibers and starch-based resin. *Proceedings of the 3rd Japan-Canada Joint Conference on New Applications of Advanced Composites (JCJC-III)*. pp. 19–27, 2003

[9] Takagi, H. & Ichihara, Y., Effect of fiber length on mechanical properties of "green" composites using a starch-based resin and short bamboo fibers. *JSME International Journal*, **Series A, 47**, pp. 551–555, 2004.

[10] Takagi, H., Biodegradation behaviour of starch-based "green" composites reinforced by Manila hemp fibers. *Proceedings of 3rd International Conference on Eco-Composites*, pp. 14.1–14.6, 2005.

[11] Takagi, H., Kako, S., Kusano, K. & Ousaka, A., Thermal conductivity of PLA-bamboo composites. *Proceedings of 4th International Workshop on Green Composites (IWGC-4)*, pp. 150–152, 2006.

[12] Russell, H. W., Principles of heat flow in porous insulators. *Journal of American Ceramic Society*, **18(1–12)**, pp. 1–5, 1935.

[13] Ochi, S., Takagi, H. & Niki, R., Mechanical properties of heat-treated natural fibers. *Proceedings of 1st High Performance Structures and Composites*, pp. 117–125, 2002.

[14] Japan Standards Association, (eds). *JIS Handbook (Japanese) construction II-2007*, Japan Standards Association, 2007.

[15] Japan Society of Mechanical Engineering, (eds). JSME Heat Transfer Engineering Data 4th Ed., Japan Society of Mechanical Engineer, 1986.