Heat transfer analyses of natural fibre composites

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Abstract

This paper reports a typical functional property of natural fibre reinforced polymer composite; namely green composites, especially transverse thermal insulation properties (along the thickness direction). This functionality is mainly derived from the inherent internal morphology of natural fibre. The thermal transfer property of polymer composites is one of the most important functional issues for material design in heat-related applications. Normally, the thermal conductivity of natural fibre is much lower than that of conventional mineral fibres such as glass fibre and carbon fibre. Therefore better thermal insulation performance is easily attained by mixing with natural fibres in polymer composites. In addition, the thermal properties of the natural fibre composites can be controlled not only by changing the thermal conductivity values of matrix but also by changing the internal microstructure of the natural fibre.
Keywords: natural fibre composites, thermal conductivity, lumen, abaca, bamboo, unidirectional composites.

1 Introduction

In recent years, a lot of research has been carried out to develop environmentally friendly polymer composites, namely green composites [1–10]. Many types of green composites have been proposed until now; however most of them have been composed of biodegradable polymer and natural fibre. Therefore this type of green composite shows fully-biodegradable nature [1], thus their waste problems are not serious and sometimes we don't have to take care of the green composites' waste after usage, because they can be completely biodegraded by the action of microorganisms. Another advantage of green composites is that

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they can be made from yearly renewable resources, such as corn, potato, and various plant fibres. So this type of bio-based green composites is regarded as a carbon neutral, renewable material.

Most studies on natural fibre composites have been focused on their mechanical performances, because the natural fibre composites in the early stage were considerably weaker than conventional structural composites; namely glass fibre-reinforced plastics (GFRP). Additionally researchers have tried to fabricate the natural fibre composites by using wide variety of methods such as press-forming, injection moulding, and filament winding methods. Due to such efforts, the mechanical performance increased to almost the same strength level, and various moulding methods were established as well.

It is well known that the natural fibres have a unique microstructure that is called 'lumen'. This lumen is usually filled with air, thus the natural fibres have a tube structure. This internal microstructure is an origin of unique functional properties of natural fibre composites. We reported that the thermal conductivity of poly lactic acid/bamboo green composites is smaller than those of GFRP and that the thermal conductivity of bamboo green composites is approximately equal to that of woods, as compared with the same density level [11]. Liu *et al.* [12, 13] have reported the relationship between thermal conductivity of natural fibre composites and the size of lumen by experimentally and theoretically.

The purpose of this paper is to explore the detailed thermal conductivity information on two different natural fibres; namely abaca and bamboo fibres. Using the simulation results reported by Liu *et al.* [12], we estimate the thermal conductivity of solid part of natural fibres. The estimated data was slightly higher than reported data for natural fibres.

2 Experimental methods

2.1 Materials

Abaca fibres were supplied from Toho Tokusyu Pulp Co., Japan. The abaca fibre was mechanically extracted from abaca plant in the Philippines, and no surface treatment was used. The average sizes of the abaca fibre were a length of about 1.4 m and diameter of about 200 μm. Bamboo fibres were extracted by a steam explosion method as reported elsewhere [11, 14]. The bamboo fibre was also used as-received condition, namely no-surface treatment. The colour of the bamboo fibre changed from light brown to dark grown after steam explosion treatments due to oxidation reaction of lignin in bamboo fibres. The average sizes of the bamboo fibre were a length of about 350 mm and diameter of about 200 μm. Low viscosity epoxy resin was used as a matrix (JER819, Mitsubishi Chemical Corporation, Japan).

2.2 Composites preparation method

Natural fibre composites reinforced by unidirectional abaca fibres or bamboo fibres were fabricated by a resin transfer moulding technique as reported elsewhere [15]. The low viscosity epoxy resin was flowed into a specially designed transparent mould by using a rotary resin pump. The size of the sample obtained was 100x100x10 mm in average.

2.3 Thermal conductivity measurement

There are several methods to measure thermal conductivity of composite plate. In this study, we used a steady-state method with reference plate [15]. After establishing a steady-state condition (as shown in Fig. 1), the transverse thermal conductivity of a sample plate, K can be calculated from the thermal conductivity of a reference plate, K_r and thickness of sample, X_s and reference plates, X_r, and also temperature differences among the sample and reference plates, ΔT_s and ΔT_r as follows:

$$K = K_r \cdot \frac{X_s}{X_r} \cdot \frac{\Delta T_r}{\Delta T_s}, \tag{1}$$

where the temperature differences ΔT_s and ΔT_r are defined as follows:

$$\Delta T_s = T_1 - T_2, \tag{2}$$

and

$$\Delta T_r = T_2 - T_3. \tag{3}$$

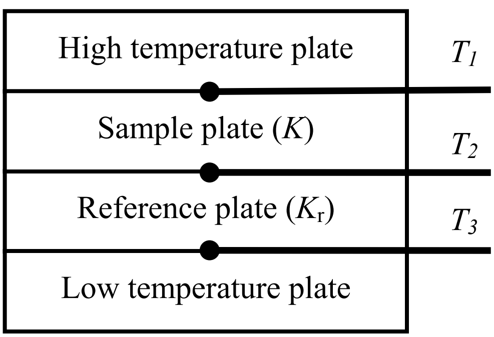

Figure 1: Schematic illustration of steady-state method [15].

2.4 Theoretical calculation of thermal conductivity using unit cell model

The two-dimensional square arrayed pipe filament (SAPF) unit cell model [12] was applied to calculate the transverse thermal conductivity of the unidirectional natural fibre composites (Fig. 2). The validity of this model that is based on thermal-electrical analogies was already indicated by Liu *et al.* [12, 13]. The most important factors affecting the transverse thermal conductivity are the lumen size ($\alpha = r_L/r_f$), thermal conductivity ratio ($\beta = K_f/K_m$), and fibre volume fraction (V_f); where r_L and r_f are radius of lumen and fibre, K_f and K_m are thermal conductivity of fibre solid part and matrix.

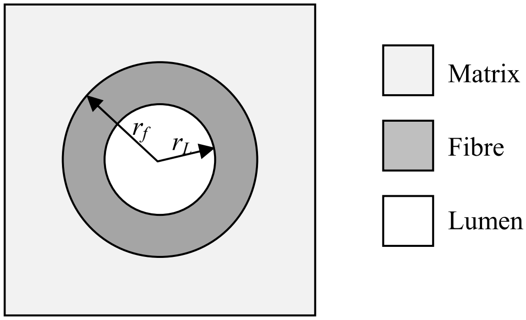

Figure 2: Schematic diagram of two-dimensional SAPF unit cell model [12].

3 Results and discussion

The measured thermal conductivity data for the two composites reinforced by abaca and bamboo fibres are listed in Table 1. In the case of bamboo fibre-reinforced composites, the thermal conductivity increases with increasing fibre volume content, on the other hand that of abaca fibre-reinforced composites decreases showing an opposite dependence. The reason for this irregular dependence is derived from the air filled in the lumens in the abaca fibres [13].

Table 1: Measured thermal conductivity data.

Abaca fibre composites		Bamboo fibre composites	
Vf (%)	K (W/mK)	Vf (%)	K (W/mK)
0.0	0.298	0.0	0.298
13.4	0.292	7.0	0.307
24.9	0.273	14.4	0.309
-	-	22.42	0.317

Figure 3 shows the relationship between thermal conductivity and fibre volume content as a function of α [12]. It should be noted that the dependency on fibre content depends strongly on the lumen size, namely the value of α. Even when $\beta > 1$, the decreasing dependence is obtained for the composites reinforced natural fibre with large lumen; i.e. large α.

From the photomicrograph of abaca and bamboo fibres [15], the α values for abaca and bamboo fibres are approximately 0.7 and 0.3, respectively. From Fig. 3, we can draw a graph (Fig. 4) showing the relationship between thermal conductivity ratio, K/K_m and β. It can be seen that the thermal conductivity of the composites, K increases with increasing β, and that this K value becomes larger in the case of smaller α.

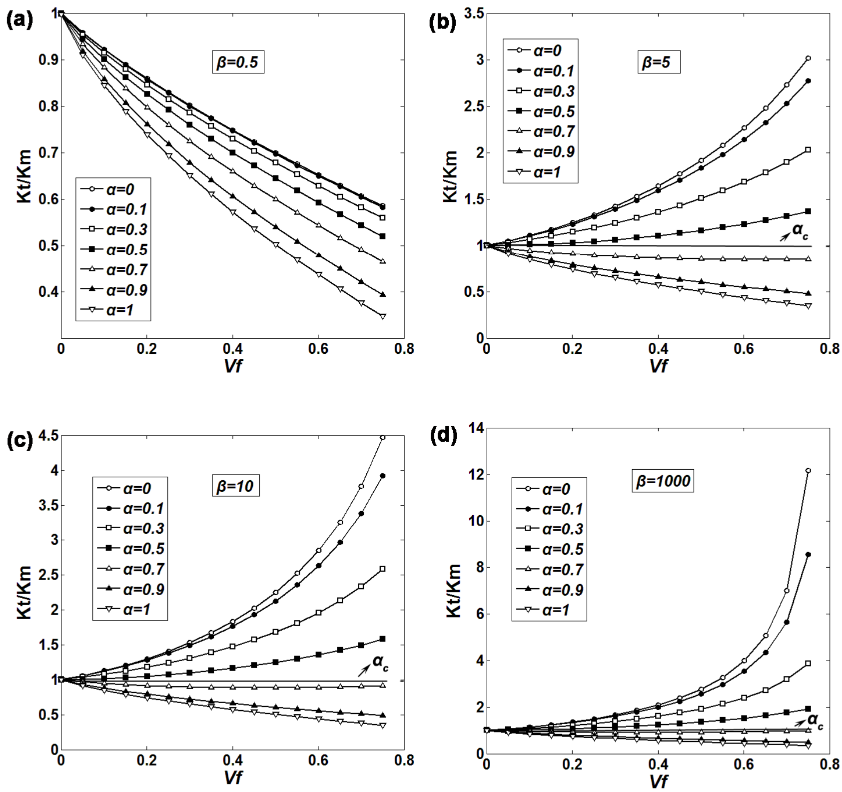

Figure 3: Calculated thermal conductivity from SAPF unit cell model [12].

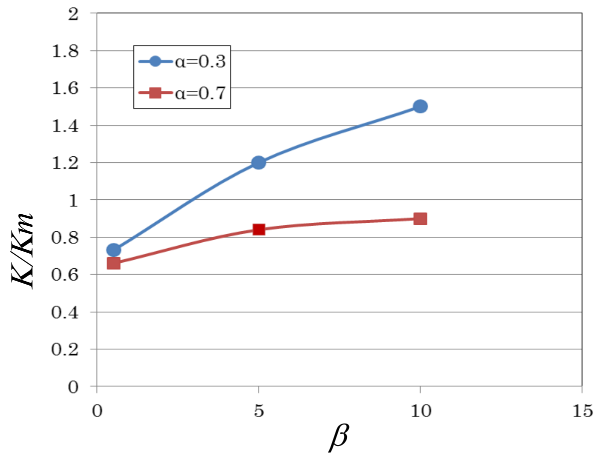

Figure 4: Relationship between thermal conductivity ratio, K/K_m and β.

As shown in Table 1, the thermal conductivity values for the composites reinforced by abaca and bamboo fibres, K_{exp} at fibre volume fraction of 0.4 are calculated to be 0.256 W/mK and 0.317 W/mK, respectively. The thermal conductivity of epoxy resin used as matrix was 0.298 W/mK [12]. Thus, K_{exp}/K_m values for abaca and bamboo fibre-composites become 0.859 and 1.064, respectively. From Fig. 3, the β values for the composites reinforced by abaca and bamboo fibres are estimated to be 6.0 and 3.3, and corresponding thermal conductivity for the solid part of abaca and bamboo fibres are 1.788 W/mK and 0.983 W/mK, respectively. These values are higher than reported value for cotton, 0.54 W/mK, because this value is for the overall value of the cotton fibre with lumen. However, Shimazaki *et al*. [16] reported that the cellulose nanofibre composites have high thermal conductivity values, and showing the qualitatively same dependence.

4 Conclusions

In summary, the thermal conductivity of solid part of abaca fibre and bamboo fibre was evaluated from experimental results and theoretical calculations. We found that the thermal conductivity for the solid part of abaca fibre and that of bamboo fibre are 1.788 W/mK and 0.983 W/mK, respectively.

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