Oil-Palm Fiber Reinforced Binary Composites: Evaluation of Effective Thermal Conductivity

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Abstract

Effective thermal conductivity (ETC) of oil-palm fiber (OPF) reinforced binary phenol formaldehyde (PF) composites have been evaluated using theoretical models. Surface morphology of OPF has been analyzed using scanning electron microscope (SEM) and Composites having various volume percentages of OPF have been studied. ETC of the composites is affected by the percentage of fiber present in the composite and surface topology of the fiber. The effective thermal conductivity of the composites obtained through theoretical models has been compared with the experimental results. ETC of these composites have been measured experimentally at room temperature and normal pressure employing a non-steady state method known as the Transient Plane Source (TPS) technique.

Key words: *Thermal conductivity, fiber percentage, TPS, oil palm fiber, composites.*

Introduction

In past two decades polymer composites containing natural fibers have been gaining considerable attention in literature and industry due to better understanding of wood plastic interaction[1-4]. Composites are widely used in electronic systems due to ease of manufacturability and lightweight coupled with low cost. During operation electronic systems produce a lot of heat that must be dissipated in order to keep the elements at suitable temperature for their reliable operation. An increase in the temperature of about 10^0 C reduces the mean life-time of the element by a factor of two[5]. Therefore the thermal performance of module packages is very important for the right application of the electronic systems. Due to the increasing use of the composite materials in electronic industry, the determination of the effective properties such as ETC and thermal diffusivity of these composites are of great importance in effective design and application. ETC of binary composites is comprised of the contribution from both the phases. The careful choice of the fiber matrix pair and fabrication method can yield a composite material with desired set of properties.

Many attempts have been made to replace or partially substitute synthetic fibers by lignocellulosic fibers[6-8]. These fibers are biodegradable and less abrasive than synthetic fibers. Moreover these composites display good set of mechanical properties[9-11]. All these aspects make their use quite tempting. Keeping this in mind we have reinforced different percentages of OPF in phenol formaldehyde (PF) matrix to fabricate binary composites. This paper is an attempt to predict the ETC of binary composites with the help of different existing theoretical models and compare them with our experimental results. Experimental results of the ETC have been published by the authors[12] elsewhere.

Materials and Methods

The resole type phenol formaldehyde resin was supplied by West coast polymers Pvt. Ltd., Kannur, Kerala India. The solid content of the resin was 50 ± 1 % and caustic soda was used as the catalyst during manufacturing. Oil palm empty fruit bunch (OPEFB) fibers were obtained from Oil India Limited, Kottayam Kerala, India. The OPEFBs were subjected to the retting process to remove the pithy material and the fibers were dried. Fibers size of 40mm was used to prepare the randomly oriented mats. Composites having 20, 30, 40 and 50 weight percentage of the fibers were been prepared. The composites were fabricated by hand lay- up followed by compression moulding at 100 ^{0}c for about 30 minutes. Measurement of ETC of all the composites has been done at room temperature and normal pressure using Transient Plane Technique[12] (TPS).

Thermal Conductivity Models

Many theoretical and empirical models have been proposed to predict the ETC of binary composites. According to the well-known geometrical model the ETC of the composites is given by

$$\lambda_e = (\lambda_f)^{\phi} (\lambda_m)^{(1-\phi)} \qquad (1)$$

Where, λ_e is the ETC of the composite. λ_f and λ_m are the thermal conductivities of the fiber and the matrix respectively. Volume percentage of the fiber is represented by ϕ.

Maxwell[13] used the mean field approach to evaluate the effective thermal conductivity. He used the fact that the path of heat in one phase is perturbed by the presence of the other phase. Babanov[14] derived an expression for the case of cubes in simple cubic arrangement. His expression was quite close to the Maxwell's equation.

$$\lambda_e = \frac{\lambda_m \left[\lambda_m + \phi^{\frac{2}{3}}(\lambda_f - \lambda_m)\right]}{\left[\lambda_m + \phi^{\frac{2}{3}}(\lambda_f - \lambda_m)\left(1 - \phi^{\frac{2}{3}}\right)\right]} \qquad (2)$$

Brailsford and Major[15] provided a field approach, which was also related to Maxwell's equation and is given by

$$\lambda_e = 1/4[(2-3\phi)\lambda_m + (3\phi-1)\lambda_f] + \sqrt{[8\lambda_f\lambda_m + \{(2-3\phi)\lambda_m + (3\phi-1)\lambda_f\}^2]} \qquad (3)$$

Brailsford and Major's approach was said to be appropriate where the second phase is represented by the random combination of the isolated particles and a continuous conducting 3D-net.

Verma et. al.[16] modifies the phase averaging approach of Hadley[17] to obtain the following expression for the ETC as

$$\lambda_e = (\lambda_m[\lambda_f + F(1-\phi)(\lambda_m - \lambda_f)])/(\lambda_m - \{1 + F(1-\phi)\}(\lambda_m - \lambda_f)) \qquad (4)$$

Where $F = \exp[-\Psi(\lambda_m/\lambda_f)^{1/3}$ and $\Psi = 1$, for the case of spherical inclusions and $\Psi < 1$ for non-spherical inclusions.

Hamilton and Crosser's[18] formula to evaluate the ETC is

$$\lambda_e = (\lambda_m [\alpha + (``(" - 1) - (``(" - 1)(1 - \alpha)\phi])/([\alpha + (``(" - 1) - (1 - \alpha)\phi) \quad (5)$$

Where $\alpha = (\lambda_f/\lambda_m)$ and $\Psi = 3/n$. n is defined as the ratio of the surface area of the sphere (with a volume equal to that of the particle) to the surface area of the particle.

Recently Q. Z. Que[19] has introduced a model to evaluate the ETC of the carbon nano-tubes reinforced composites.

$$\lambda_e = \frac{\lambda_m[1 - \phi + 2\phi A \ln B]}{[1 - \phi + 2\phi C \ln B]} \quad (6)$$

where $A = \lambda_f/(\lambda_f - \lambda_m)$, $B = (\lambda_f + \lambda_m)/2\lambda_m$, $C = \lambda_m/(\lambda_f - \lambda_m)$

Though this model has been derived for nano-composites but does not contain any special feature/parameter which characterizes nano-composites. Hence this model may also be applicable to any binary composite.

ETC evaluated using above models along with experimental results are shown in the table below. All values of ETC (λ_e) are in W/mK. Volume percentage of the oil-palm fiber in the PF matrix is represented by ϕ. λ_e (I), λ_e (II), λ_e (III), λ_e (IV), λ_e (V) and λ_e (VI) are the results obtained through the geometrical model, Babanov's model, Brailsford and Major's model, Verma et.al Model, Hamilton and Crosser's model and Q.Z. Que model respectively. λ_e (Exp.) represents the experimental results.

Table 1. Evaluated ETC from the above models along with experimental results.

S.No.	ϕ	λ_e (I)	λ_e (II)	λ_e (III)	λ_e (IV)	λ_e (V)	λ_e (VI)	λ_e (Exp.)
1.	0.27	0.309	0.312	0.311	0.308	0.311	0.313	0.304
2.	0.38	0.297	0.300	0.299	0.297	0.299	0.297	0.301
3.	0.49	0.286	0.289	0.288	0.286	0.288	0.294	0.293
4.	0.59	0.277	0.279	0.278	0.276	0.279	0.282	0.286

Results and Discussion

Model results of the ETC of the composites having different volume percentages of the oil-palm fiber are plotted in figure 1 along with the Experimental values. Figure 1 infers that all the model results are in excellent agreement with the experimental data. In Babanov's model the arrangement of the dispersed phase is simple cubic. Brailsford and Major's formula for ETC is related to the Maxwell's equation, which was originally derived for a very dilute solution of dispersed sphere in a matrix. The equation works excellently even for fibers. Moreover, these equations give appropriate results even for high concentrations of the dispersed phase (OPF). The reason attributed to the above fact is that these models do not contain any parameter dependent on the size and shape of the dispersed phase. This suggests that shape and size of the particles are of secondary importance.

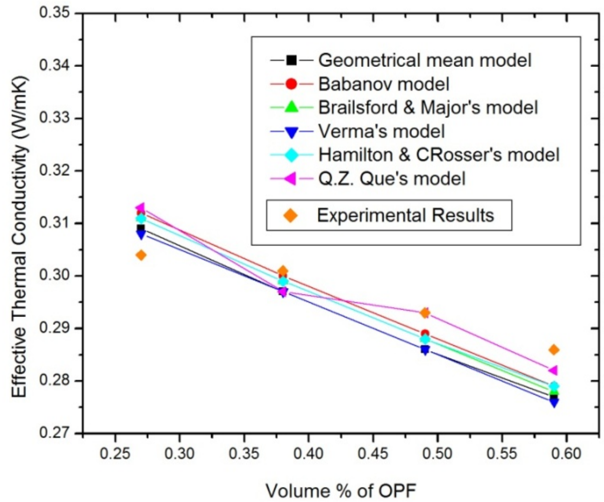

Figure 1 Variation of ETC with volume percentage of OPF.

In Hamilton & Crosser's model[18] and Verma's model[16] Ψ contains the information about the shape of dispersed particles/fibers. In this calculation we have used $\Psi = 0.857$ for oil-palm fibers as these fibers are not spherical but can be assumed of cylindrical shape. Though both these models contain the dependence on the shape of the dispersed phase, the results are not very different from the other theoretical models. This fact is attributed to the fact that size and shape of dispersed medium are important either at low temperatures or if the thermal conductivity of the dispersed phase is much higher (100 times) than the thermal conductivity of the matrix. Meredith and Tobais[23] observed no effect of the size and shape of the dispersed phase for quartz and diamond composites, which is supportive of the above fact.

Q.Z. Que model[18] for ETC is basically designed for the carbon nano-tubes (CNT). CNT's have high thermal conductivities. In spite of this fact the results obtained by this model are not different as obtained by the other existing models. According to Que existing models to evaluate the ETC of composites cannot be used for evaluation the ETC of the CNT reinforced composites due to certain restrictions. But the reverse does not seem to be true as this model fits our experimental results quite well. The reason lies in the fact that Que's Model is based on the Maxwell's theory.

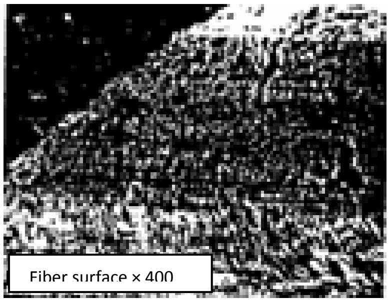

Figure 2. Surface of OPF (×400)

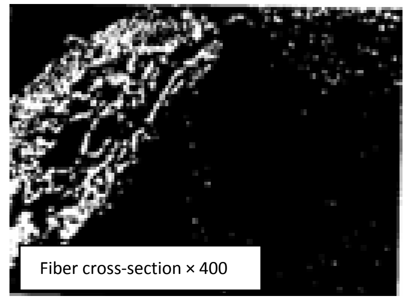

Figure 3. Cross-section of OPF (×400)

The scanning electron micrograph (SEM) of the surface and cross section are of oil-palm fibers are shown in figure 2 and Figure 3 respectively. SEM of the OPF surface is porous and shows the presence of a waxy layer. Cross- section of the oil palm fiber shows a lacuna like opening in the middle. Presence of pores gives better adhesion between the OPF and the PF resin but the effect of the waxy layer opposes it. Waxy layer decreases the interaction between the OPF and the PF resin. Looking at the decreasing trend of the ETC with the increasing volume percentage of the OPF predicts that the presence of waxy layer dominates the porous structure of the OPF's. As the volume percentage of the OPF increases in the composites, there is less interaction between the PF resin with the OPF's and hence the ETC of the composites decreases.

Conclusions

All the theoretical models fit our experimental data very well. Most remarkable fact is that the model specially derived for the CNT fits the experimental data correctly. ETC of the composites shows a decreasing trend with the increasing volume percentage of the OPF. Surface topology of the OPF plays an important role explaining this trend of the ETC.

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