Study on Physical and Thermal Characteristic of Natural Fibre Reinforced Polymer Composites

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Abstract: In the present work, thermal conductivity of pine wood dust (150µm mesh size) filled epoxy composites have been studied experimentally & empirically. The thermal conductivity values of PWD filled epoxy composites were calculated experimentally using guarded heat flow meter method in accordance with ASTME-1530 standard. The effects of density and filler content on the thermal conductivity of composite products were investigated and found that thermal conductivity values increases in a linear manner with density and decreases in non-linear manner with filler (PWD) content. An empirical investigation for describing thermal conductivity of PWD filled epoxy composite was compared with the experimental results and has a good agreement with it. It was also compared with other empirical equations for predicting thermal conductivity values of wood and found that thermal conductivity values obtained from empirical investigation consistently has lower values than other empirical equations. It is found that the composite density values calculated theoretically are not equal to the experimentally measured values. This difference is a measure of voids and pores present in the composites. It is also found that with the increase in filler (PWD) content from 0 vol% to 35.9 vol%, the theoretical as well as measured densities decreases by about 22%.

Keywords: *Thermal conductivity, Epoxy, Pine wood dust, Natural fibre composites, Guarded heat flow meter, Empirical.*

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1. Introduction

Natural fiber reinforced polymer composites are hybrid with their properties, with characteristics of both natural fibres and polymers. Incorporation of natural fibers in to polymer is now a standard technology to improve the insulating and mechanical properties of polymer. The fibres resulting from wood, animals, leaves, grasses and other natural sources are commonly used as reinforcement in composites used for various applications, like automotive (interior and exterior), building, ship, packaging *etc.*, due to their unusual properties compared to other synthetic fibres. Advances in manufacturing techniques in natural fibre-reinforced composites have allowed the car industry to utilize these composites in interior trimmings. Besides the environmental benefits, compared to glass fibre composites, the natural fibre reinforced composites with the equivalent performances have higher fibre content, resulting in less pollution from synthetic polymer matrix and much lighter weight, reducing the amount of driving fuel in automotive applications.

The improvement of the insulating properties of composites can be determined by measuring their thermal properties i.e. the values of thermal conductivity. Generally thermal conductivity is a property which has ability to conduct heat of materials. It plays an important role in determining their heat conduction/insulation capability. Some studies have investigated the thermal conductivity of wood based composites, but few have explored the thermal conductivity of natural fibre and thermoplastic composites. Russell[1]and Maxwell[4] theoretical models have been widely applied for predicting thermal conductivity of multi-phase composites. Maclean[2], Kollman[3],Wikes[6], Tenwolde et al.[8] and Kamke[9] reviewed the empirical equations for predicting the thermal conductivity of wood and wood based panel products. Steinhagen[5] reviewed the thermal conductivity of wood from -40^{0}C to 100^{0}C and found that the thermal conductivity of wood increases in a linear manner with temperature and density. He also found little difference between its value in tangential and radial directions. Siau[7] reported thermal conductivity in longitudinal direction to be 2.5 times greater than the transverse direction. Suleiman et al. [10] investigated the thermal conductivity of wood in both longitudinal and transverse direction in the temperature range of 20-100^{0}C. Their results showed that thermal conductivity was about 1.5 times more in the longitudinal direction than in transverse direction due to non-homogenous nature of wood. Liu et al.[11] concluded that 0.185 (W/m-K) is a suitable value in the transverse direction for the cell wall thermal conductivity of Manila hemp fibre based on theoretical and finite element methods. Mohapatra et al.[12] found that the thermal conductivity of pine wood dust-filled epoxy composites decreased as filler content increased.

The objective of this research is to investigate the effect of density on the thermal conductivity of pine wood dust filled epoxy composites with varying proportions of pine wood dust filler. An empirical equation was fitted for describing the thermal conductivity of these composites and was compared with other empirical equations derived for wood based materials and theoretical models for multi-phase mater

2. Theoretical Investigations

The composite is usually prepared based on calculation of weight fractions or volume fractions. In this research volume fraction was taken into consideration. The density of the composite is found out by rule of mixtures. As per rule of mixtures, the density of the composite is obtained by

$$\rho_c = \rho_m v_m + \rho_f v_f \qquad [1]$$

Where ρ_c= Density of the composite, ρ_m= Density of the matrix, ρ_f= Density of the filler.

If v_f= Volume fraction of filler, V_f = Volume of the filler, V_m = Volume of the matrix and V_v = Volume of voids, then the volume fraction of the filler

$$v_f = \left[\frac{V_f}{V_f + V_m + V_v}\right] \times 100 \text{.......................................[2]}$$

Where Volume of the composite

$$V_c = V_f + V_m + V_v \text{...[3]}$$

The measured density (ρ_a) of the composite was determined experimentally by using water immersion technique. Considering theoretical density and actual density, the volume fraction of the void is calculated as follows

$$V_v = \frac{\rho_c - \rho_a}{\rho_c} \text{...[4]}$$

Table.1 Properties of Pine wood dust and Epoxy

Properties	Pine wood dust	Epoxy
Density (g/cc)	0.52	1.1
Thermal conductivity (W/m-K)	0.068	0.363

3. Experimental Investigations

3.1 Materials

The pine wood dust (collected from Jaylaxmi Saw Mill Limited. Kolkotta) of 150µm mesh size measured through sieve shaker were considered as filler material in fabrication of the composite. Epoxy (LY 556 and Hardner HY 951 supplied by Hindustan Ceiba Geigy India Ltd) has been used as matrix material. A metallic mould has been developed in house to cast for thermal conductivity testing. After mixing epoxy and pine wood dust in proper ratio the composite was cast by pouring into the split mould. The cast of each composite was cured under a load of about 50kg for 24hours before it was removed from the mould. Then this cast was post cured in air for another 24hours after removing out from the mould.

3.2 Experimental procedure

A guarded heat flow meter has been developed for thermal conductivity measurements. This is achieved by using a thermal conductivity testing system Unitherm Model 2022.(Fig.1) The tests are in accordance with ASTM-E-1530 standard. The sample and a heat flux transducer (HFT) shown in (Fig. 2) are sandwiched between two flat plates controlled at different temperatures to produce a heat flow through the stack. A cylindrical guard surrounds the test stack and is maintained at a uniform mean temperature of the two plates, in order to minimize the lateral leak of heat. In Unitherm 2022 the heat flux transducer measures the Q value. At steady state, the difference in temperature between the surfaces contacting the specimen is measured with temperature sensors embedded in the surfaces along with output from the heat flow transducer. Taking these values with known cross sectional area and the sample thickness, the thermal conductivity is calculated using equation 1.

$$Q = KA\left[\frac{T_1 - T_2}{L}\right] \text{............................(5)}$$

Fig.1 The Unitherm 2022

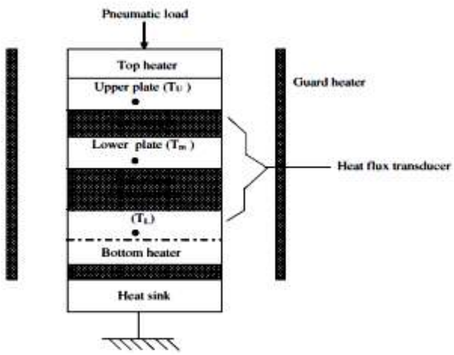

Fig.2 Schematic model showing the testing arrangement

4. Empirical Investigation

Considering a linear relationship between thermal conductivity and temperature and density, a nonlinear relationship with pine wood dust content and applying least square method, a relationship was represented to describe the thermal conductivity (k) of pine wood dust (PWD) filled epoxy composite.

$$k = 0.00020236T + 0.2085\rho + 0.00188V_f - 0.00002094V_f^{\,2} - 0.04919 \text{...........[6]}$$

The empirical Eq.(6) can be used to describe the effects of temperature and density on the thermal conductivity of pine wood dust (PWD) filled epoxy composite with varying volume fractions of PWD. Coefficient of temperature for the pine wood dust filled epoxy composite (0.00020236) is close to that reported for wood fibre composite (0.0002 by Tenwolde et al. [8]). The density coefficient of pine wood dust filled epoxy composite (0.2085) is also close to that reported for wood based panels (0.2001 by Maclean [2] and 0.1941 by Tenwolde et al. [8] shown in Table.2). If we set the temperature and the PWD content at 25^{0}C and zero in

Eq. (5), the thermal conductivity of epoxy can be predicted using Eq. (6).

$$k = 0.2085\rho - 0.044131 \quad [7]$$

Table. 2 Empirical equation for predicting the thermal conductivity of wood based composite panels

Equation name	Empirical equation
Maclean [2]	$k = 0.2001\rho + 0.02376$
Kollmann [3]	$k = 0.184\rho + 0.217500$
Wikes [6]	$k = 0.1686\rho + 0.02582$
Tenwolde et al.[8]	$k = 0.1941\rho + 0.01864$

5. Thermal conductivity model

The thermal conductivity of a composite material depends on the fiber, resin materials, fiber volume fraction, orientation of the fiber, direction of heat flow and operating temperature. Many theoretical and empirical models have been proposed to predict the effective thermal conductivity of two phase mixtures.

Series Model (Rule of Mixture):

$$\frac{1}{K_c} = \frac{1-v_f}{K_m} + \frac{v_f}{K_f} \quad (8)$$

Where subscript, c- composite, m- matrix, f-filler and v_f - volume fraction

Parallel Model:

Parallel model:

$$K_c = (1-v_f)K_m + v_f K_f \quad (9)$$

Where K_c - Thermal conductivity of composite, K_m- Thermal conductivity of matrix, K_f- Thermal conductivity of filler and v_f - is the volume fraction of the filler. Most of the experimental results were found to fall in between the two models. However the lower bound model is usually closer to the experimental data compared to the rule of mixture, which brought to a number of different models derived from the basic series model.

Maxwell Model:

Maxwell [3] is the one who developed first theoretical model for two phase system. The derived equation is given by Eqn. 10

$$K_c = K_m\left[\frac{K_f + 2K_m + 2v_f(K_f - K_m)}{K_f + 2K_m - v_f(K_f - K_m)}\right] \quad (10)$$

6. Results and discussion

6.1 Density and volume fraction of voids

The theoretical and measured densities of the composites along with the corresponding volume fraction of the voids are shown in fig.3 and fig.4 respectively. From fig.3 it is found that the composite density values calculated theoretically are not equal to the experimentally measured values. This difference is a measure of voids and pores present in the composites. It is also found that with the increase in filler (PWD) content from 0 vol% to 35.9 vol%, the theoretical as well as measured densities decreases by about 22%. On the other hand, it is found from fig.4 that with increase in filler (PWD) content the void fraction or porosity increases from 0.73% to 5.68%. The density of a composite depends on the relative proportion of matrix and reinforcing materials and this is one of the most important factor for determining the properties of the composites. The voids significantly affect some of the mechanical properties and even the performance of composites in the workplace. Higher void contents usually means lower fatigue resistance, greater susceptibility to water penetration and weathering. It is understandable that a good composite should have voids. Table 3 shows the values of theoretical and measured densities along with void fraction.

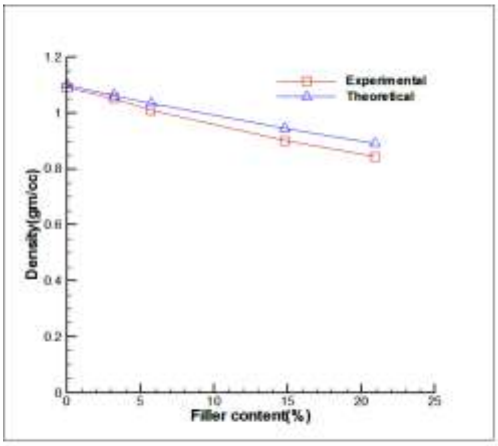

Fig.3 Comparison of density values for different methods

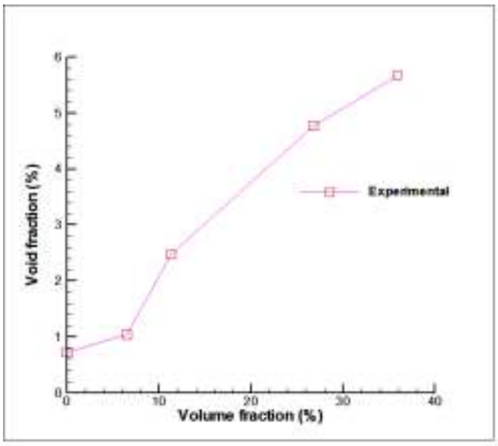

Fig.4 Voids of composites as a function of filler content

Table 3 Measured and Theoretical densities

Composites	Measured density (g/cc)	Theoretical density (g/cc)	Volume fraction of voids %
Neat Epoxy	1.092	1.100	0.73
Epoxy+6.5 vol.% PWD	1.052	1.063	1.04
Epoxy+11.3 vol.% PWD	1.009	1.034	2.47
Epoxy+26.8 vol.% PWD	0.901	0.944	4.77
Epoxy+35.9 vol.% PWD	0.844	0.896	5.68

6.2 Experimental results

Fig.5 presents a comparison on the thermal conductivity values obtained from the experimental work with empirical equation (6) for same size of pine wood dust and same filler contents i.e 6.5%,11.3%,26.8% and35.9% Volume fraction respectively. On comparison it was found that the thermal conductivities of the polymer composites were decreased as the volume fraction of the reinforcement increased, but the distribution of thermal conductivities are slightly higher in case of experimental study on comparison to empirical analysis. They are very closer at higher filler content i.e. at 35.9%. It is also interesting to note that the addition of PWD results in reduction in thermal conductivity of epoxy resin and there by improves its thermal insulation capability. Table 4 shows thermal conductivity comparison between two methods

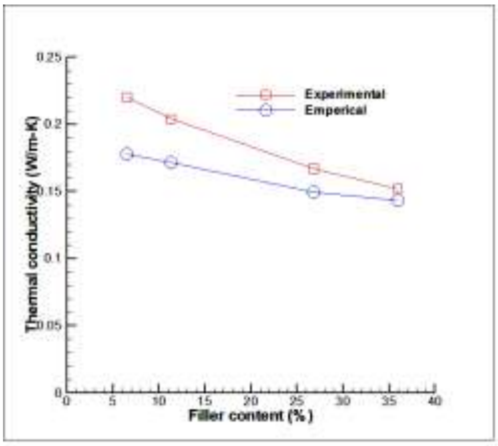

Fig.5. Thermal conductivity of epoxy composites as a function of filler content

Table 4 Thermal conductivity comparison between two methods

Composites	Effective thermal conductivity (W/m-K)	
	Experimental	Empirical
Epoxy+6.5 vol.% PWD	0.220	0.1776
Epoxy+11.3 vol.% PWD	0.204	0.1716
Epoxy+26.8 vol.% PWD	0.167	0.1497
Epoxy+35.9 vol.% PWD	0.152	0.1433

6.3 Comparison models

Fig.6(a) shows the comparison of thermal conductivity of PWD filled epoxy composites obtained from [Eq. (7)] with other empirical equations derived for wood thermal conductivity (Wikes, 1981; Kollmann, 1951; MacLean, 1941; TenWolde et al., 1988), and Table 2 gives the empirical equations for predicting the thermal conductivity of wood and its composites at dry conditions. From this figure it is found that the thermal conductivity of all models increases linearly with increase of density. It is also found that the thermal conductivities obtained from Maclean, Kollman, Wikes andTenwolde empirical equations overestimate the values of thermal conductivity obtained from equation 7. Results described by Eq. (7) are conservative compared to other empirical equations for predicting thermal conductivity of wood and its composites (Fig. 6(a)). Differences in the chemical constituents and structure of PWD filler could be the potential source for these variations. Fig. 6(b) compares the empirical Eq. (6) with theoretical models. For theoretical models, the PWD is recognized as one phase, and its thermal conductivity is 0.068W/m-K. The matrix phase is epoxy, and its thermal conductivity is tested as 0.363 W/m-K. All the theoretical models along with experimental results predict the upper limits of composites thermal conductivities obtained from empirical equation(6).The parallel and series models predict the upper and lower limits of composite's thermal conductivity. The thermal conductivities values of PWD filled epoxy composites obtained from Eq.(6) is very closer to the series model at higher volume fraction i.e. 35.9% of filler (PWD). The values of thermal conductivity associated with each method for individual composite with two components i.e. pine wood dust (PWD) filler and epoxy are given in Table 5 and Table 6 respectively.

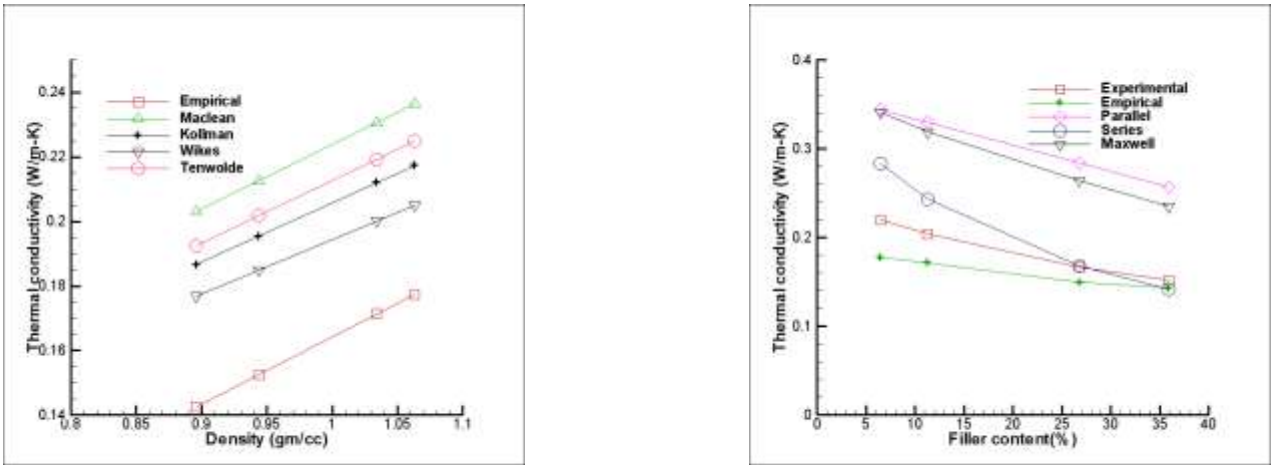

Fig. 6. Comparison of predictions by empirical equation derived in this study with (a) other empirical equations for wood-based panels and (b) theoretical models derived for two-phase composites

Table 5 Comparison of empirical equation derived in this study with other empirical equations

Composites	Effective thermal conductivity (W/m-K)				
	Maclean	Koll man	Wikes	Tenwolde	Empirical
Epoxy+6.5 vol.% PWD	0.2364	0.2173	0.2050	0.2249	0.1776
Epoxy+11.3 vol.% PWD	0.2306	0.2120	0.2001	0.2193	0.1716
Epoxy+26.8 vol.% PWD	0.2126	0.1954	0.1849	0.2018	0.1497
Epoxy+35.9 vol.% PWD	0.2030	0.1866	0.1769	0.1925	0.1433

Table 6 Thermal conductivity values of composites obtained from different methods

Composites	Effective thermal conductivity (W/m-K)				
	Parallel	Series	Maxwell	Experimental	Empirical
Epoxy+6.5 vol.% PWD	0.344	0.283	0.341	0.220	0.1776
Epoxy+11.3 vol.% PWD	0.330	0.243	0.319	0.204	0.1716
Epoxy+26.8 vol.% PWD	0.284	0.168	0.264	0.167	0.1497
Epoxy+35.9 vol.% PWD	0.287	0.142	0.235	0.152	0.1433

6. Conclusion

Thermal conductivity of pine wood dust (PWD) filled epoxy composites was tested using a thermal conductivity testing system Unitherm Model 2022 in accordance with ASTM-E-1530 standard. Results showed that thermal conductivity of pine wood dust filled epoxy composites linearly increases with density, and nonlinearly decreases with PWD content. An empirical equation that includes temperature, density and PWD content was fitted to describe the thermal conductivity. Thermal conductivity of PWD filled epoxy composite is limited by parallel and series models, and is closer to series model with higher PWD content. The density of a composite depends on the relative proportion of matrix and reinforcing materials and this is one of the most important factors for determining the properties of the composites. The results of this research provide vital information for the heat transfer of PWD filled epoxy composites during manufacturing and in use as end products.

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