Effect of cenosphere on thermal conductivity of bamboo fibre reinforced composites

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Abstract

The present study attempts to explore the possibilities of utilising industrial waste as filler material in bamboo fibre reinforced composites. Cenosphere, a mixture of alumina and silicon rich industrial waste produced during burning of coal in thermal power plants, is used as filler material in this study. It's use in composites would address environmental and economic concern arising in storage and handling of enormous quantity of waste discharged by the thermal power plants. In order to determine the heat insulation property of this polymer composites with varying bamboo fibre (18, 28, 33, 43 wt%) and cenosphere filler (0, 2.5, 3, 4.5, 6 wt%) content, thermal conductivity test is performed by using Lee's disc apparatus. Experimental results reveal that with the increase in fibre loading, the thermal conductivity of the composite decreases and it is minimum at 43 wt% of fibre. It is also found that introduction of cenosphere fillers on bamboo fibre reinforced composite results in further reduction of its thermal conductivity. Hence improved thermal insulation property of these composites can be gainfully utilised in insulation application. The thermal conductivity of these composites is also evaluated by using Finite Element Method, which is in good agreement with that of experimental results. The test results for thermal conductivity are also in good agreement with various models available in the literature. Copyright © 2017 VBRI Press.

Keywords: Nano- cenosphere, bamboo fibre, epoxy, thermal properties, finite element method.

Introduction

Bamboo fibre, a popular natural fibre is used as reinforcements in polymer composites. Faster growth rate and abundant availability of bamboo gives a socio-economic benefit and gives an eco-friendly composite material. Being hydrophilic in nature the bamboo fibre leads to improper adhesion with matrix, hence reduces its mechanical properties and dimensional stability. As result it affects its long term outdoor applications. In order to overcome this problem, there are number methods available in the literature for surface treatment of fibre to improve the interfacial adhesion between fibre and matrix and hence increase the mechanical properties of these composites **[1-2]**. It is also observed that the properties of fibre reinforced composites under varying loading conditions can also be modified by changing the stacking sequence of lamina and number of lamina **[3]**. Addition of different fillers **[4]** or synthetic fibres **[5]** into bio fibre composite has significant influence on its performance. The incorporation of micro or nano-sized spherical filler to the fibre surfaces is a new emerging technique to get improved properties **[6]**. But the incorporation of such filler is a costlier affair. Cenosphere, which comprises of micro-hollow spheres, is used as filler material in the composites **[7-8]**. It is an industrial waste produced enormously during the burning of pulverized coal in thermal power plants. Due to its fine dispersion, homogeneity, inertness and chemical stability, it can be a potential filler in polymer matrix composite. There are number of research on cenosphere filled composite and its influence on mechanical properties of the composites **[8-10]**. But its application to the bio-fibre reinforced composite has gained less attention till date.

Along its mechanical strength, heat insulating value of the composite material decides its specific applications. Thermal conductivity is one of the important properties in specialised application such as wall, partition, roofing etc for determining its heat insulating value. There are several instances of investigation of thermal conductivity of polymer composites filled with metallic fillers **[11-12]** and inorganic fillers **[13]**. It is observed that thermal conductivity of the composites materials is much lower than of metals and ceramics **[14]**. Hence the prediction of thermal conductivity of composites has been focus of attention of many researchers to get composites for suitable applications. There exist different experimental techniques like hot-wire method **[15]**, lee's disc method **[16]** to measure thermal conductivity of polymers composites. Lee disc's method is simplest method and used for bad conducting material. This method is used to measure thermal conductivity of the present composites.

Different theoretical and empirical models have been developed for modelling thermal conductivity of composite material system **[17-18]**. A proper selection of theoretical and empirical model is required to obtain the thermal conductivity of composites. Progelhof et al **[19]** have given a review paper on prediction of thermal conductivity of composites of two phase system using different theoretical and empirical models highlighting their applicability. To validate different theoretical as well as empirical model with experimental data which are based on two phase composite system are used to determine the thermal conductivity of the present composite system. Finite element method (FEM) is also be used to determine thermal conductivity of composite material system **[20]**. For this, ANSYS is a tool for finite element method analysis of the thermal properties measurement of the composite materials.

Addition of filler into fibre reinforced composite (three phase composite system) is an emerging trend in the composite manufacturing and study of their thermal conductivity is essential. There are several instances to study the effect of filler on thermal conductivity on fibre reinforced composites. Modified thermal properties are observed after dispersion of nanoclay in vinyl ester-glass fibre composite by Chandradass et al **[21]**. Extensive research has been carried out on thermal conductivity of natural fibre reinforced composite materials **[22-24]**. The thermal conductivity of sisal-polyethylene, glass-polyethylene and sisal/glass hybrid fibre-reinforced polyethylene has been studied at cryogenic to high temperature by Kalaprasad et al **[25]**. Similarly, the effect of fibre volume fraction and fibre surface treatment on thermal properties of banana/ sisal hybrid fibre reinforced composites are studied by Idicula et al **[26]**. The thermal properties of banana/glass hybrid polyester composites are also studied by Agarwal et al **[27]**. They take advantage of both natural and synthetic fibres to produce hybrid composite and modify their thermal conductivity. But there is no investigation into the thermal conductivity of filler filled natural fibre reinforced composites.

In viewing this, the objective of present study is to determine the thermal conductivity of bamboo fibre reinforced polymer composites. And also study the effect of adding varying wt% of cenosphere in fibre reinforced composite system. Selection of the cenosphere is not only address the concern regarding environment issue but also its shows its capability to blend with fibre reinforced composite.

Experimental

Materials

The cenosphere, an industrial waste used as a filler in the present composite. It is procured from Micro Minechem Pvt Ltd, India. It is grey in colour which is hollow spherical in structure. The particulate filler, cenosphere has particle density 0.45 - 0.80 gm/ml and size 60 - 94 micron. The bamboo (Dendrocalamus strictus) mat (110 x 110 mm) used for this work has been procured from Luit Nirman India, Assam. The thickness and width of each slivers are 0.2 mm and 3 mm which are woven into mats. The matrix system consists of a medium viscosity epoxy resin Diglycidyl Ether of Bisphenol A (DGEBA) and a room temperature curing hardener Triethylene Tetra-amine (TETA) purchased from ATUL India Ltd. Density of the epoxy resin is 1.1 gm/cc.

Methods

To improve the adhesion between fibre and matrix, NaOH treatment is carried out for the bamboo fibre. Using these treated fibre, the composite with different wt% of cenosphere filler have been prepared by hand layup technique. Thermal conductivity test is performed by Lee's disc apparataus.

NaOH treatment

The bamboo mats are cut to desired dimension of 110 mm x 10 mm and cleaned with fresh water for removal of dust particles from its surface. The cleaned mats are treated with NaOH solution of 5% concentration at room temperature **[28]** and thoroughly washed in distilled water and thereafter neutralized with dilute HCl solution, followed by repeated wash with distilled water to reach neutralisation. These mats are then put into an oven for 24 hours at 60^0 C. The NaOH treatment is meant for improving the interlocking between fibre and matrix so as to improve the interfacial adhesion between fibre and matrix.

Fabrication of composites

Conventional hand lay-up technique is adopted for fabrication of the bamboo-epoxy composite at room temperature. Low temperature cured epoxy matrix and its corresponding hardener are mixed in a ratio of 10:1 by weight. A number of bamboo composite samples are prepared using different number of lamina of bamboo fibre mats (3, 5, 7 and 9) as reinforcement and varying weight percent of cenosphere filler (0, 1.5, 3, 4.5 and 6%). Under uniform load composite samples are placed in the mould and cured at room temperature for 24 hours before it is removed from the mould. Teflon sheet and silicon spray are used in order to avoid adhesion between mould and composite samples for easy removal of composite. Finally, these samples are further cured in air for another 24 hours after removing out of the mould. The fabricated composite samples are cut into the dimension to suit thermal testing.

Experimental set-up

Fig. 1 represents a schematic diagram of Lee's disc apparatus which is designed and used to measure the thermal conductivity of bamboo-epoxy composite with different weight percentage of fibre/filler content and with/without alkali treatment. A heat source is used in the setup to maintain constant temperature. Two copper disc of thickness 10 mm and diameter 50mm are placed over the induction heater to hold the composite sample in between them. The temperatures of both copper discs are obtained by using thermocouples. If k is the thermal conductivity of the composite sample, Fourier Law expresses the conductive heat transfer as

$$Q = \frac{kA\,(T_1 - T_2)}{d} \quad (1)$$

where, T_1 and T_2 are temperatures of copper disc 1 and 2 respectively. T_1-T_2 is the temperature difference across the composite sample. A and d are the area and thickness of the composite specimens.

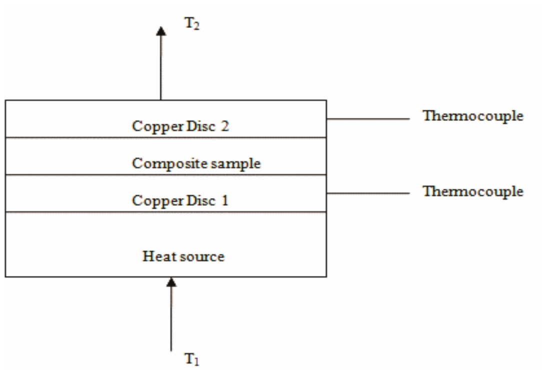

Fig. 1. Schematic diagram of Lee's disc apparatus.

The rate of heat loss by metallic disc to surrounding under steady state is

$$Q = mC_p\left(\frac{dT}{dt}\right)_{T_2} \quad (2)$$

Where m, Cp and dT/dt is the mass, heat capacity and rate of cooling of copper disc at temperature T_2.

Combining the equation (1) and (2), thermal conductivity k of the composite sample can be written in the following form:

$$k = \frac{mC_p\left(\frac{dT}{dt}\right)_{T_2} \times d}{A(T_1 - T_2)} \quad (3)$$

Thermal conductive models

Effective thermal conductivity of composite transverse to the fibre direction can be predicted by the rules of mixture (ROM) as given by following relation **[29]**.

$$\frac{1}{k} = \frac{v_f}{k_f} + \frac{(1 - v_f)}{k_m} \quad (4)$$

where, k and v is effective thermal conductivity and volume fraction respectively and subscripts f and m show corresponding fibre and matrix, respectively. For the fibre reinforced composites with dispersed filler particles in matrix, the thermal conductivity can be predicted by using equation (4) by replacing k_m with the effective thermal conductivity of the modified matrix k'$_m$. The modified equation is

$$\frac{1}{k} = \frac{v_f}{k_f} + \frac{(1 - v_f)}{k'_m} \quad (5)$$

Following models are considered in the present study for estimating the effective thermal conductivity k'$_m$ for filler mixed matrix.

Maxwell's model [**19**]:

$$k'_m = k_m \times \frac{2k_m + k_p - 2(k_m - k_p)v_p}{2k_m + k_p - (k_m - k_p)v_p}$$

Bruggeman's model [**19**]:

$$1 - v'_p = \frac{k_p - k_m}{k_p - k_m}\left(\frac{k_m}{k'_m}\right)^{\frac{1}{3}}$$

Neilson's model [**19**]:

$$\frac{k'_m}{k_m} = \frac{1 + A'Bv'_p}{1 - B\varphi v'_p}$$

where,

$$B = \frac{k_p / k_m - 1}{k_p / k_m + A}, \quad \varphi = 1 + \frac{(1 - \phi_{max})v'_p}{\phi_{max}^2} \quad \text{and} \quad A' = k_{en} - 1$$

The value of Einstein constant k_{en}, A' =f(geometry of particle), and ϕ_{max} (maximum packing factor) can be obtained from reference **[19, 30]**.

Where $v'_p = \frac{v_p}{v_m + v_p}$, v_p and v_m are volume fraction of filler and matrix respectively.

Finite element method (FEM)

FEM is first introduced in the year of 1956 by Turner *et al.* **[31]**. It is a tool which is capable of solving a wide range of complex problems. It has got considerable attention in recent decades to analyse the thermal, mechanical properties or stress and failure analysis of fibre reinforced composite system **[32,33]**. There are several authors who have used FEM to determine the effective thermal conductivity of particulate filled polymer composites **[20, 34-35]**.

Thermal conductivities of bamboo-epoxy composite with and without cenosphere filler are numerically estimated by using finite element programme ANSYS. In order to model the problem, a section of the fibre as shown in the **Fig. 2** is considered for the modelling.

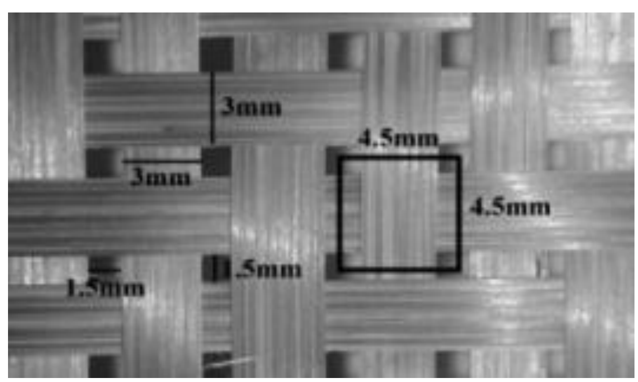

Fig. 2. Section of the fibre used in the ANSYS modelling.

A three dimensional physical model of the composite with different layers of matrix and fibres are shown in the **Fig. 3** which is known as representative volume element of the composite material.

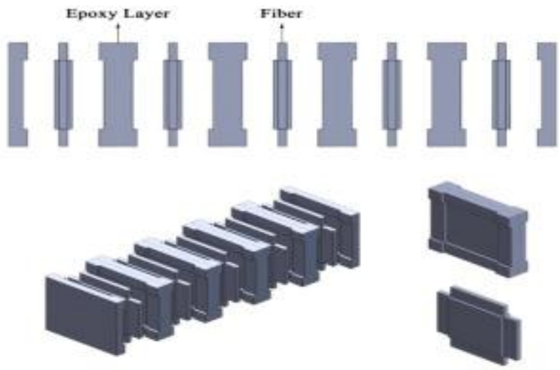

Fig. 3. Representative volume element of the composite material.

In ANSYS, analysis of the heat conduction in representative volume element of the composite material, the temperatures are noted as T_1 and T_2 at the nodes along the surfaces ABCD and WXYZ respectively as shown in the **Fig. 4**. Adiabatic conditions are assumed on the other surfaces of the cell where it is parallel to the direction of the heat flow. The temperatures at the nodes in the interior region is to be obtained with the help of ANSYS. It is also able to find the temperatures at adiabatic boundaries.

Effective thermal conductivity of the bamboo composites is calculated by using the results of the thermal analysis of composite with different fibre and filler loading. The representative volume element cell with the dimensions along x, y and z-axis are of Z_x, Z_y and Z_z. The thermal conductivity is calculated using the following relation **[34]**:

$$k_c \frac{\Delta T}{Z_z} = \frac{1}{S}\sum_i \sum_j k_{ij} x_i y_j \left(\frac{\partial T_{ij}}{\partial z}\right)$$

With $s_{ij} = x_i y_j$

$\sum_i \sum_j s_{ij} = S$ and $k_{ij}= k_m$ for matrix and k'_m for matrix with filler k_f for fibre

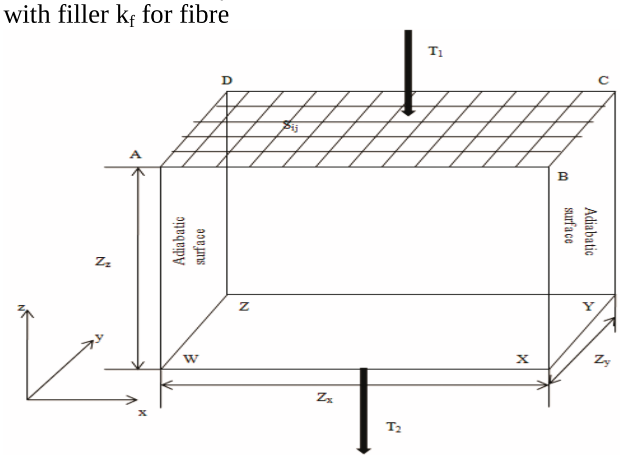

Fig. 4. Boundary conditions.

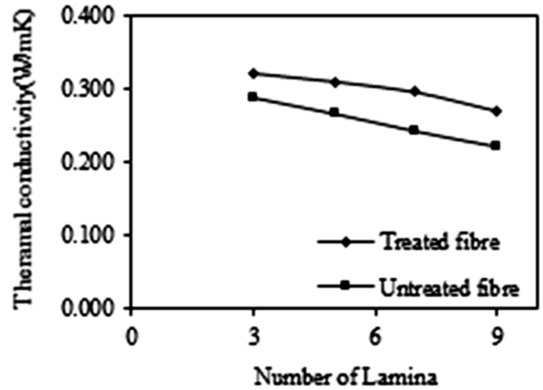

Fig. 5. The thermal conductivity of the composites prepared with treated and untreated fibres for different number of lamina.

Results and discussion

Effect of fibre treatment and fibre content

The thermal conductivity of the composite with treated and untreated fibres are shown in **Fig. 5**. The results indicate that alkali treated fibres give better thermal conductivity than the untreated fibre composites. This may be due to the reason that the treatment removes lignin, wax and oil from the surface of the fibres **[36]**. This in turn improves the area of contact between fibre and matrix. The removal of hydroxyl group from the fibres increases its crystalline due to better packing of cellulose chain. **Fig. 6(a)** shows X-ray diffraction pattern of bamboo fibre samples before and after alkali treatment. The decrease in diffraction peaks indicates higher degree of crystalline with alkali treatment. This also supports above observation. The surface modification of fibre increases the area of contact between the fibre and matrix leading to increase in thermal conductivity **[24]**.

With the increase in the number of layers of fibre which in turn increases the wt % of fibre in the bamboo epoxy composites, its thermal conductivity is seen to be decreased as shown in **Fig. 5**. Minimum thermal conductivity is observed at 43.0 wt. % of fibre content. A similar observation has been found in the case of banana fibre composite by Paul *et al* **[23]**.

Thermal insulation property of these composites can be gainfully utilised in insulation applications which not only fulfils its objective, but also give good appearance. To decrease energy consumption in air conditioned buildings, the present composite system with insulation properties may be an option to be considered as building components. From the Figure, it is clearly observed that the thermal conductivity of the bamboo-epoxy composites is mainly affected by bamboo fibre content. This indicates that bamboo fibre has lower thermal conductivity than that of epoxy matrix. **Table 1** shows the calculated thermal conductivities of the composites according to ROM model. The results of experiment and FEM model are also presented in the same table. The errors associated with ROM and FEM values with respect to experimental value lies in the range of -1.5 to 4.8 % and -2.5 to 4.6 % respectively.

Table 1. Thermal conductivity values for composite of different lamina number.

Composite with Different Number of lamina	Wt. % of Fibre	Experimental value	ROM (Percentage error with respect to the experimental value)	FEM
3	18	0.321	0.311 (3.1)	0.312 (2.8)
5	28	0.310	0.295 (4.8)	0.297 (4.6)
7	33	0.296	0.288 (2.7)	0.290 (2.0)
9	43	0.270	0.275 (-1.7)	0.278 (2.5)

Effect of cenosphere filler

In order to show the effect of cenosphere filler on thermal conductivity of bamboo epoxy composite, composites are prepared with 7 layers of bamboo fibre mats (33 wt. % of fibre) using different weight percentage of cenosphere filler (0, 1.5, 3, 4.5, 6 wt%). It is observed that 33 wt% of fibre has optimum mechanical property **[9]**, hence this composition is taken for further study on effect of cenosphere addition. **Fig. 6(b)** shows the results of FEM and experimental value of thermal conductivity. Results indicate that incorporation of cenosphere results in reduction of thermal conductivity of composite. The increase of filler from 0 wt. % to 1.5 wt. % in the matrix results in decrease in thermal conductivity of the order of 1.0 %. The change in thermal conductivity from 0 to 6.0 % filler is about 2.6 %. But further addition is not advisable in making composite material as its mechanical strength is reduced on 6.0 wt. % filler addition **[9]**.

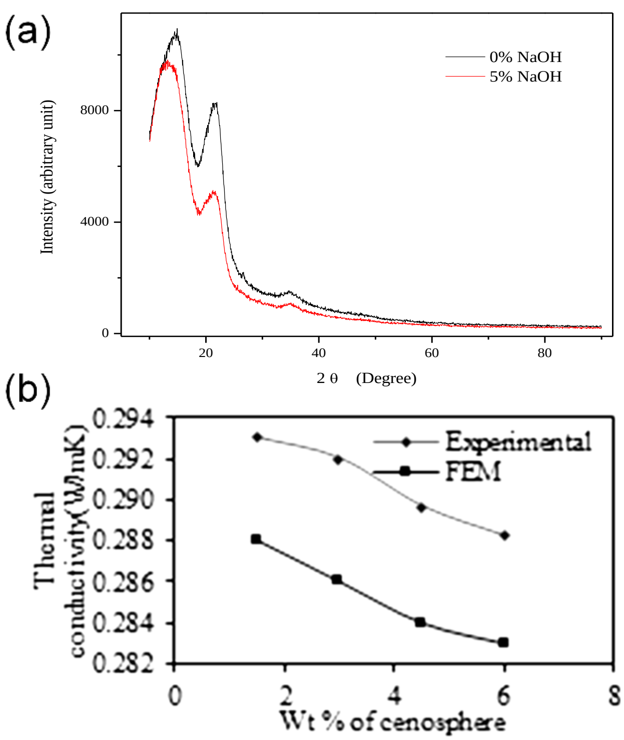

Fig. 6. (a) X-ray diffraction pattern of bamboo fibre samples before and after alkali treatment; (b) FEM and experimental value of thermal conductivity of composite with different wt.% of cenosphere.

The thermal conductivity values of 7 layered composite with varying wt. % of cenosphere are obtained from various models. Its experimental results are compared with different models and the percentage errors associated with each model for composite with different weight percentage of filler are shown in **Table 2**. The different models which are used to obtain thermal conductivity for the three phase composite system are suitable as the % error is in the range of 1.6-2.6 %. The results obtained from FEM are also close to the experimental measured values of effective thermal conductivity and the % error is in the range of 1.4-1.6 %.

Addition of cenosphere in bamboo-epoxy composites has shown improved thermal insulation property as well as the mechanical property **[9]**. Its successful industrial application in composite will be a new avenue to address not only the environmental but also economic concern arising in storage and handling of enormous quantity of waste discharged by the thermal power plants.

Table 2. Percentage errors with respect to experimental value.

Composite with Different wt% of cenosphere	ROM (%)	Maxwell's model	Bruggeman's model	Neilson's model	FEM (%)
	Percentage error with respect to the experimental value				
1.5	2.161	2.049	2.049	2.335	1.686
3.0	2.236	2.018	2.018	2.596	1.605
4.5	2.055	1.737	1.737	2.613	1.619
6.0	2.010	1.601	1.601	2.793	1.435

Conclusion

Thermal conductivity of the bamboo-epoxy composite with varying numbers of lamina and weight percentage of cenosphere filler are investigated. The conclusions are: Thermal conductivity of bamboo-epoxy composite is improved by surface treatment of fibre with alkali. Increase in number of layers, decrease thermal conductivity of these composites and value lies in the range between 3-16 %. Addition of cenosphere filler to these composites decreases their thermal conductivity. The change in thermal conductivity with addition of 0 to 6% filler is about 2.6%. The thermal conductivity values obtained from present FEM analysis agree well with the experiment. The experimental results of these composites are compared with various theoretical models which are available in the literature, indicate the suitability of models to these types of composites.

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