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Determination of Thermal Conductivity of Polymer Composites Filled with Solid Glass Beads

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Abstract

A numerical simulation of the heat-transfer process within epoxy matrix composites filled with solid glass beads (SGB) is made by using finite element analysis (FEA). A commercially available finite-element package ANSYS is used for this numerical analysis. Three-dimensional spheres-in-cube lattice array models are constructed to simulate the microstructure of composite materials for various SGB content ranging from about 1 to 18 vol % and the effective thermal conductivities (K_{eff}) of the composites are estimated. The results show that the FEA simulated effective thermal conductivity decreases almost in a parabolic manner with increase in the volume fraction of the SGB fillers in the composites. Finally, the simulations are compared with measured K_{eff} values obtained from experiments. Guarded heat flow meter test method is used employing the instrument Unitherm™ Model 2022 as per ASTM-E1530 to measure the thermal conductivity of these composites fabricated by hand layup technique. This study shows that the incorporation of SGB results in reduction of heat conductivity of epoxy resin and thereby improves its thermal insulation capability. The experimentally measured conductivity values are compared with the numerically calculated ones and it is found that FEA simulations are fairly close to the measured K_{eff}.

Keywords: *Polymer Composites; Solid Glass Beads; Finite Element Analysis; Effective Thermal Conductivity; Simulation*

1. Introduction

The improved performance of polymers and their composites in industrial and structural applications by the addition of solid filler materials has shown great promise and so has lately been a subject of considerable interest. Various kinds of polymers, and polymer matrix composites reinforced with metal particles have a wide range of industrial applications such as heaters, electrodes (K. Jung-il et al, 2004), composites with thermal durability at high temperature (S.Nikkeshi et al, 1998) etc. These engineering composites are desired due to their low density, high corrosion resistance, ease of fabrication and low cost (Tavman et al, 1997 ,K.Zhu,2003), M.Rusu et al, 2001), S.Cheng et al, 1970). Increasing use of polymer composites for various applications emphasizes its importance/significance in the thermal property analysis of an engineering system. Conductivity is one such important thermal property that needs to be evaluated for any new composite system. Generally, measuring the thermal conductivity accurately is helpful to study the heat transfer process and mechanisms in composite materials. Although it can be measured by experimental methods, analytical methods and equations are often essential to predict thermal conductivities of composite materials.

Considerable work has been reported on the subject of heat conductivity in polymers by Hansen and Ho (1965), Peng and Landel (1975), Choy and Young (1977), Tavman (1991) etc. The fillers most frequently used are aluminum, copper and brass particles, short carbon fiber, carbon particles, graphite, aluminum nitride, magnetite particles etc. Progelhof et.al (1976) were the first to present an exhaustive overview on models and methods for predicting the thermal conductivity of composite systems. Procter and Solc (1991) used Nielsen model as a prediction to investigate the thermal conductivity of several types of polymer composites filled with different fillers and confirmed its applicability. While Kumlutas and Tavman (2006) carried out a numerical and experimental study on thermal conductivity of particle filled polymer composites, Patnaik et.al (2010) reported the existence of a possible correlation between thermal conductivity and wear resistance of particulate filled composites. Recently Nayak et.al (2010) have reported on the modified thermal conductivity of pine wood dust filled epoxy- based composites.

The heat transfer process in porous materials is very complicated, especially for polymer composites. It is quite important, therefore, to understand the mechanisms of heat transfer in polymer composites. For porous materials, several researchers have derived effective thermal conductivity equations based on the Maxwell expression, or established a more accurate formula for calculating the effective thermal conductivity of such materials. The models proposed respectively by Nielsen (1973) and Cheng-Vochon (1970) can better estimate the effective thermal conductivity of filled composite materials, while the Agari-Nagai (1993) equation can predict for composites with high particle loading. While Liang and Qu (1999) analyzed the thermal conductivity of a porous material with closed spherical and cylindrical holes, Suvorov et al. (1989) studied the thermal conductivity of hollow emery filled composites.

There are only a few published papers on evaluation of effective thermal conductivity of polymer composites filled with glass beads. Liang and Li (2006) reported on measurement of thermal conductivity of hollow glass-bead-filled polypropylene composites. Recently, they (Liang and Li, 2007 a) also made two-dimensional and three-dimensional finite element analysis on the heat transfer and simulated the variation of effective thermal conductivity of hollow glass microsphere filled polymer composites. Liang and Li (2007 b) further studied the heat transfer in polymer composites filled with hollow glass micro-spheres and proposed a theoretical model to predict the thermal conductivity of such composite systems. Yung et al (2009) have also reported the preparation and properties of hollow glass microsphere-filled epoxy- matrix composites. But all these studies are for polymer composites filled with hollow glass spheres and surprisingly, there is no report available on evaluation of effective thermal conductivity of solid glass microsphere filled polymer composites. In view of the above, the present work is undertaken to evaluate the thermal conductivity of epoxy- matrix composites filled with solid glass beads (micro-spheres) both experimentally as well as numerically using FEA.

2. Experimental details

2.1 Composite fabrication

Epoxy LY 556 resin, chemically belonging to the ‘epoxide’ family is used as the matrix material. Its common name is Bisphenol-A-Diglycidyl-Ether. The epoxy resin and the hardener are supplied by Ciba Geigy India Ltd. Epoxy is chosen primarily because it happens to be the most commonly used polymer and because of its low density (1.1 gm/cc) and low value of thermal conductivity (0.363 W/m K). Spherical glass beads (SGB) of 100 micron mean particle size, supplied by Glass Bead Industries India Ltd. are reinforced in epoxy resin to prepare the composites. This low temperature curing epoxy resin and the corresponding hardener (HY951) are mixed in a ratio of 10:1 by weight as recommended. The dough (epoxy filled with SGB) is then slowly decanted into the glass molds, coated beforehand with wax and a uniform thin film of silicone-releasing agent. The composites are cast in these molds so as to get disc type cylindrical specimens (dia 25 mm, thickness 5 mm). Composites of six different compositions (0, 1.4, 3.4, 6.5, 11.3 and 17.9 vol % of SGB respectively) as listed in Table 1 are made. The castings are left to cure at room temperature for about 24 hours after which the glass molds are broken and samples are released.

2.2. Experimental determination of thermal conductivity

Unitherm™ Model 2022 is used to measure thermal conductivity of a variety of materials. These include polymers, ceramics, composites, glasses, rubbers, metals and other materials of low to medium thermal conductivity. Only a relatively small test sample is required. Non-solids, such as pastes or liquids, can be tested using special containers. Thin films can also be tested accurately using a multi-layer technique. The tests are in accordance with ASTM E-1530 standard.

3. Numerical Analysis: Concept of finite element method and ANSYS

The finite element analysis (FEA), originally introduced by Turner et al. (1956) , is a powerful computational technique for approximate solutions to a variety of ‘‘real-world” engineering problems having complex domains subjected to general boundary conditions. FEA has become an essential step in the design or modeling of a physical phenomenon in various engineering disciplines. A physical phenomenon usually occurs in a continuum of matter (solid, liquid, or gas) involving several field variables. The field variables vary from point to point, thus possessing an infinite number of solutions in the domain. The basis of FEA relies on the decomposition of the domain into a finite number of sub-domains (elements) for which the systematic approximate solution is constructed by applying the variational or weighted residual methods. In effect, FEA reduces the problem to that of a finite number of unknowns by dividing the domain into elements and by expressing the unknown field variable in terms of the assumed approximating functions within each element. These functions (also called interpolation functions) are defined in terms of the values of the field variables at specific points, referred to as nodes. Nodes are usually located along the element boundaries and they connect adjacent elements. The ability to discretize the irregular domains with finite elements makes the method a valuable and practical analysis tool for the solution of boundary, initial and eigen-value problems arising in various engineering disciplines. The FEA is thus a numerical procedure that can be used to obtain solutions for a large class of engineering problems involving stress analysis, heat transfer, fluid flow etc. ANSYS is general-purpose finite-element modeling package for numerically solving a wide variety of mechanical problems that include static/dynamic, structural analysis (both linear and nonlinear), heat transfer, and fluid problems, as well as acoustic and electromagnetic problems.

4. Results and discussion

4.1. Numerical analysis

Using the finite-element program ANSYS, thermal analysis is carried out for the conductive heat transfer through the composite body. In order to make this analysis, three-dimensional physical models with spheres-in-cube lattice arrays have been used to simulate the microstructure of composite materials for five different filler concentrations. Furthermore, the effective thermal conductivities of these epoxy composites filled with SGB up to about 17.9% by volume are numerically determined using ANSYS.

4.2. Description of the problem

The determination of effective properties of composites is of paramount importance for functional design and application of composite materials. One of the important factors that influence the effective properties and can be controlled to an appreciable extent is the microstructure of the composite. Here, microstructure means the shape, size distribution, spatial distribution and orientation distribution of the reinforcing inclusion in the matrix. Although most composite possess inclusion of random distributions, great insight of the effect of microstructure on the effective properties can be gained from the investigation of composites with periodic structure. System with periodic structures can be more easily analyzed because of the high degree of symmetry embedded in the system.

A typical periodic arrangement of solid glass beads within the epoxy body is schematically shown in Fig. 1. Fig. 2 clearly illustrates the heat flow direction and the boundary conditions for the particulate-polymer composite body considered for the analysis of this conduction problem. The temperature at the nodes along the surfaces ABCD is prescribed as T_1 (=100^0C) and the ambient convective heat transfer coefficient is assumed to be 25 W/m^2-K at room temperature of 27°C. The other surfaces parallel to the direction of the heat flow are all assumed adiabatic. The temperatures at the nodes in the interior region and on the other boundaries are unknown. These temperatures are obtained with the help of the finite-element program package ANSYS. In this analysis it is assumed that the composites are macroscopically homogeneous, locally both the matrix and filler are homogeneous and isotropic, the thermal contact resistance between the filler and the matrix is negligible and the composite lamina is free from voids. The problem is based on 3D physical model and the filler arranged in a square periodic array are assumed to be uniformly distributed in the matrix.

Thermal conductivities of these SGB-epoxy composites are numerically estimated by using the spheres-in-cube model. A typical 3-D model showing arrangement of spherical fillers with a particle concentration of 1.4 vol% within the cube shaped matrix body is illustrated in Fig.3. The temperature profiles obtained from FEA analysis for the composites with particulate concentrations of 1.4, 3.4, 6.5, 11.3 and 17.9 vol % are presented in Figs 4a, 4b, 4c, 4d and 4e respectively.

The simulated values of effective thermal conductivity of the composites obtained from FEA are presented in Table 2 along with the corresponding measured values. It is noticed that the results obtained from the finite-element analysis taking sphere-in-cube composite model are reasonably closer to the measured values of effective thermal conductivity for composites of different filler content. The percentage errors associated with the FEA values with respect to the experimental values is given in Table 3. It is seen from this table that the errors associated with sphere-in-cube model simulations lie in the range 0-2 %. On comparing, it is further noticed that FEA underestimates the value of thermal conductivity, with respect to the experimental ones. However, it leads to a conclusion that for a particulate filled composite of this kind the finite element analysis can very well be used for predictive purpose in determining the effective thermal conductivity for a wide range of particle concentration.

Fig. 5 presents the variation of effective thermal conductivity (both simulated as well as measured) as a function of the SGB content in the composites. The difference between the simulated values and the measured value of conductivity may be attributed to the fact that some of the assumptions taken for the numerical analysis are not real. The distribution of SGB in the matrix body in the numerical analysis is assumed to be in an arranged manner, whereas in the fabricated composite sample, the glass beads are actually dispersed in the resin almost randomly. However, it is encouraging to note that the incorporation of SGB results in significant drop in thermal conductivity of epoxy resin. With addition of 1.4 vol. % of SGB, the thermal conductivity decreases by about 19.283 % and with addition of 17.9 vol.% of SGB the thermal conductivity decreases by about 36.914% when compared with neat epoxy resin.

5. Conclusions

This numerical and experimental investigation on thermal conductivity of SGB filled epoxy composites has led to the following specific conclusions:

- Successful fabrication of epoxy based composites filled with SGB by hand-lay-up technique is possible.
- The value of effective thermal conductivity obtained for various composite models using FEA are in reasonable agreement with the experimental values for a wide range of filler content. Hence finite element analysis can be gainfully employed as a predictive tool to determine effective thermal conductivity of these composites.
- Incorporation of SGB results in reduction of thermal conductivity of epoxy resin and there by improves its thermal insulation capability. With addition of 1.4 vol.% of SGB, the thermal conductivity drops by about 19.283% while with addition of 17.9% of SGB, a drop of about 36.9 % in the thermal conductivity is achieved.
- With light weight and improved insulation capability SGB filled epoxy composite can be used for applications such as electronic packages, insulation board, food container, thermo flasks, building materials, space flight and aviation industry etc.

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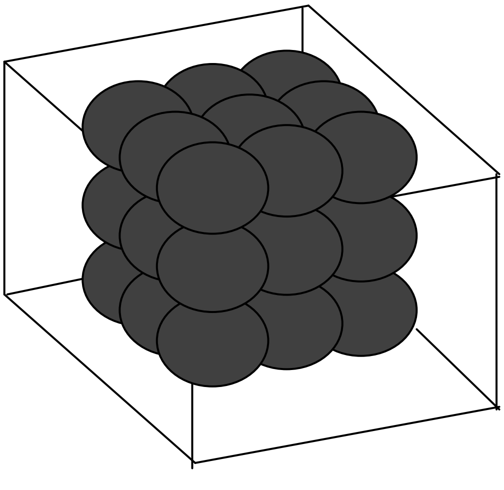

Fig .1. Schematic diagram showing a typical arrangement of SGB within the epoxy body

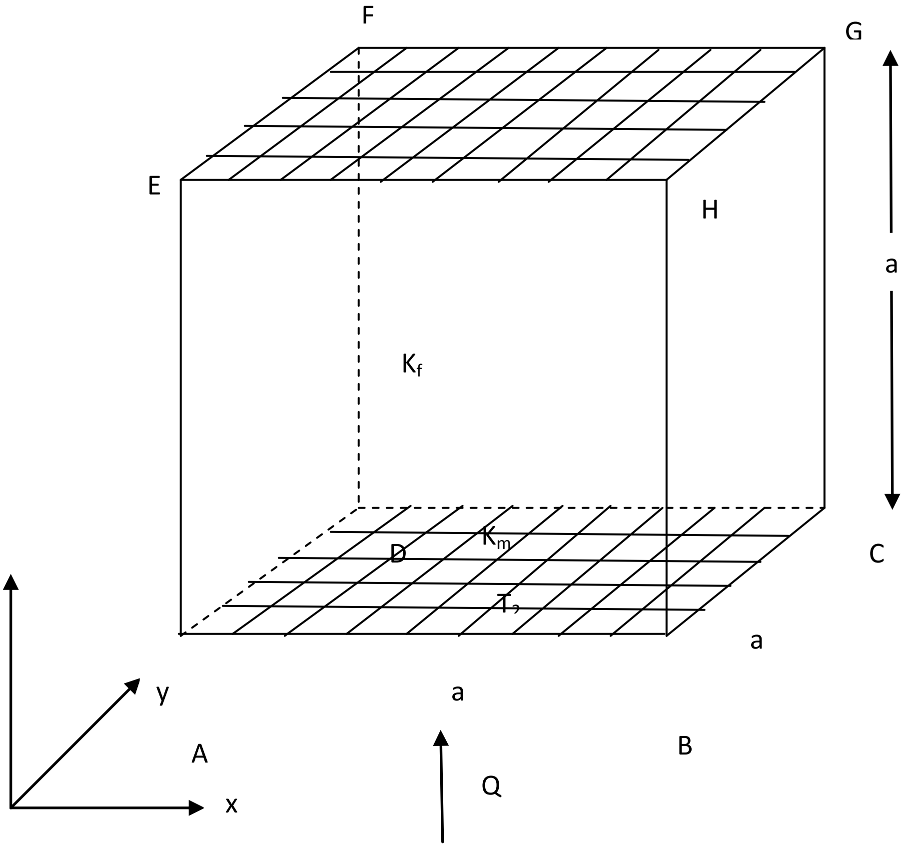

Fig .2 . The heat flow direction and boundary conditions for the particulate-polymer composite

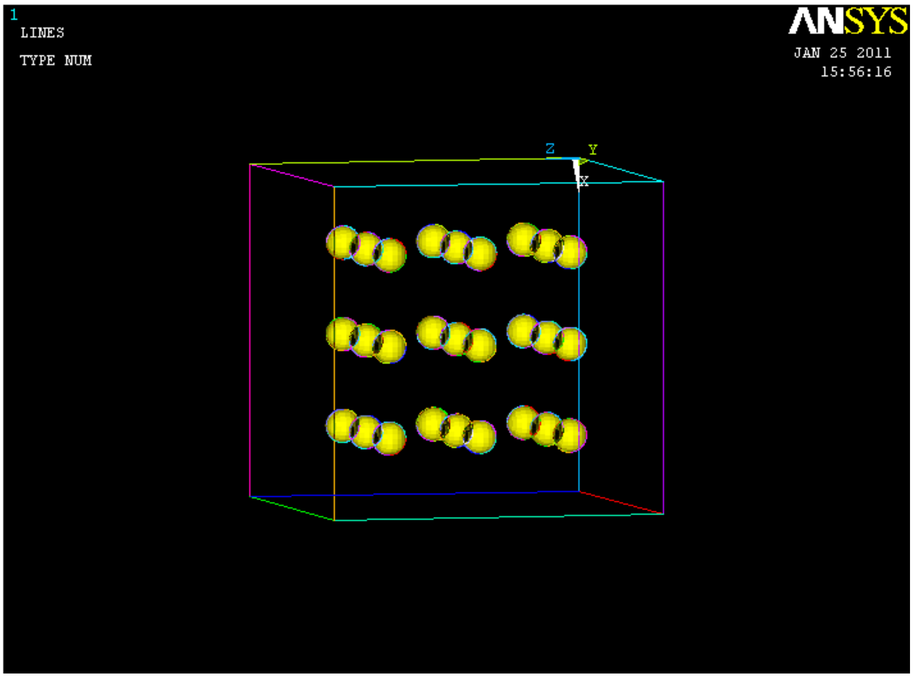

Fig. 3. A typical 3-D spheres-in-cube model with filler concentration of 1.4 vol %

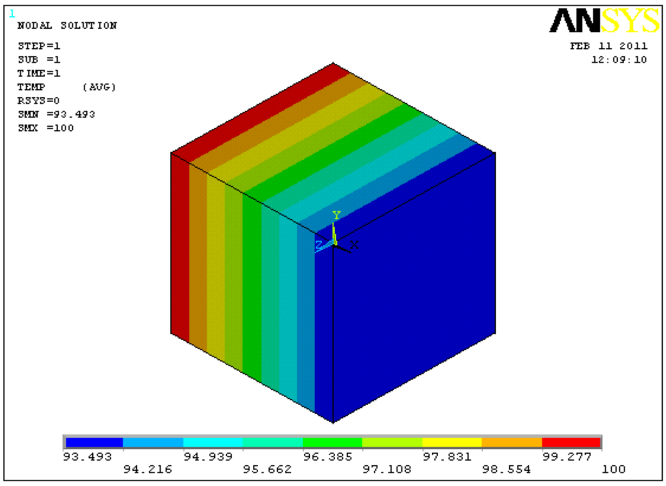

Fig .4a. Temperature profile for epoxy-SGB composite with filler concentration of 1.4 vol %

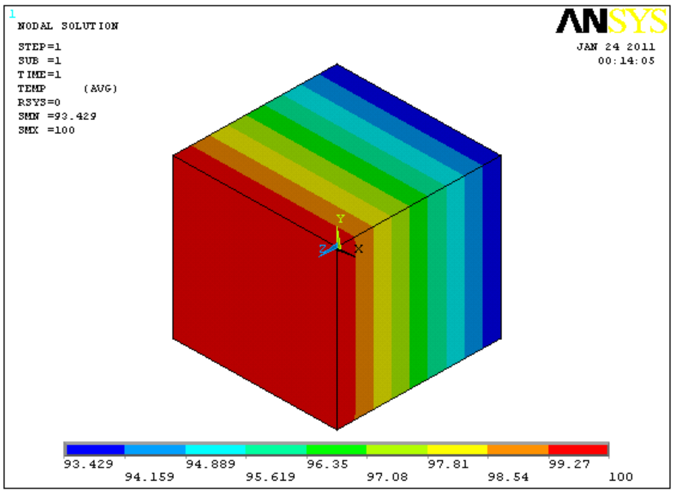

Fig .4b. Temperature profile for epoxy-SGB composite with filler concentration of 3.4 vol %

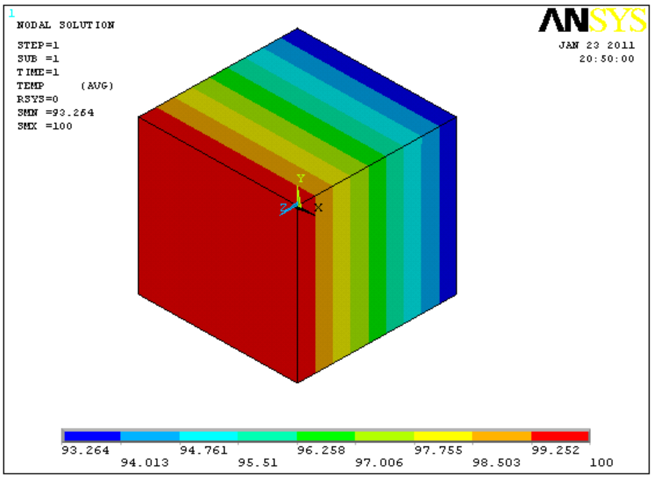

Fig .4c Temperature profile for epoxy-SGB composite with filler concentration of 6.5 vol %

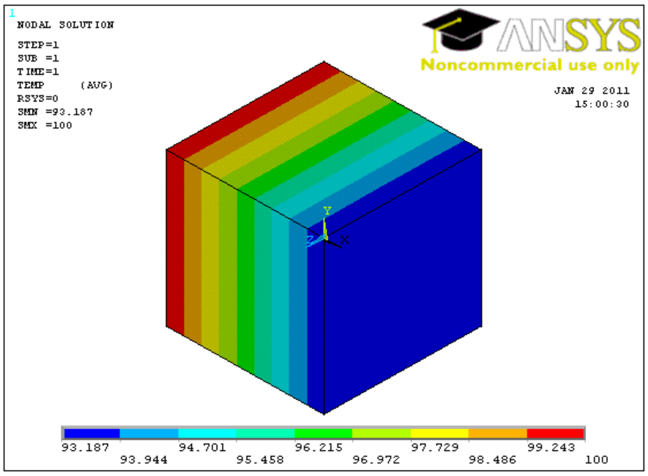

Fig.4d. Temperature profile for epoxy-SGB composite with filler concentration of 11.3 vol %

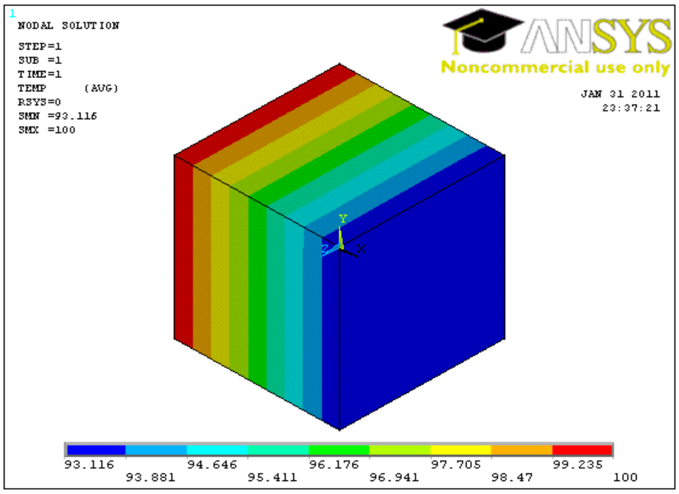

Fig .4e Temperature profile for epoxy-SGB composite with filler concentration of 17.9 vol %

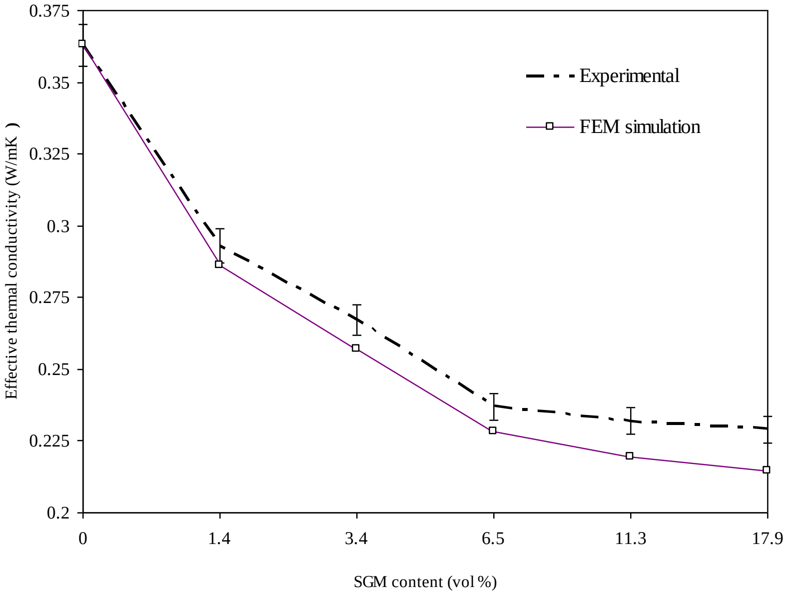

Fig.5. Variation of effective thermal conductivity with filler content

Samples	Composition
1	Epoxy + 0 vol% (0 wt%) Filler
2	Epoxy + 1.4 vol% (2 wt%) Filler
3	Epoxy + 3.4 vol% (4.5 wt%) Filler
4	Epoxy + 6.5 vol% (8.5 wt%) Filler
5	Epoxy + 11.3 vol % (15 wt%) Filler
6	Epoxy+17.9 vol% (23%) Filler

Table 1: List of particulate filled composites fabricated by hand-lay-up technique

Sample	SGB Content (vol %)	Effective thermal conductivity of composites K_{eff} (W/m K)		
		FEA (Spheres-in-cube Model)	Experimental value	Percentage errors
1	0	----	0.363	----
2	1.4	0.2862	0.293	0.7
3	3.4	0.2568	0.267	1.1
4	6.5	0.2283	0.237	0.9
5	11.3	0.2195	0.232	1.3
6	17.9	0.2145	0.229	1.5

Table 2. Thermal conductivity values for composites obtained from FEA, Experiment and the associated percentage errors with respect to the experimental value