Analytical and experimental investigation of particulate filled polymer composites with enhanced thermal conductivity

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Received 23 December 2015; accepted 26 October 2016

The present study aims at investigating an opportunity of enhancing heat conduction ability of a typical particulate filled polymer composite. A mathematical correlation for evaluating the effective thermal conductivity ($k_{\text{eff}}$) of polymer composites filled with elliptical shape particles is developed. To validate this model, high thermal conductivity aluminium powders were incorporated in the epoxy matrix for the first set of polymer composites whereas, for the second set, an industrial waste, i.e., red mud is taken as a filler material. Simple hand lay-up technique is used for fabrication purpose. Thermal conductivities of these fabricated composite samples are determined experimentally using the Unitherm\textsuperscript{TM} Model 2022 tester which works on the principle of double guarded heat flow meter method according to ASTM E1530 standard. Measured values are then compared with the values obtained from the proposed mathematical model and also with some already existing correlation. It has been observed that the results obtained from the proposed model fits well with the experimental data. An improvement of about 260\% in the value of $k_{\text{eff}}$ is recorded with addition of 25 vol\% of aluminium filler in epoxy resin whereas with similar loading of red mud, it is noticed that $k_{\text{eff}}$ increases by about 200\%. Apart from this thermal investigation, physical properties like density and void content along with morphological behaviour of the fabricated composites are also reported.

Keywords: Polymer matrix composites, Epoxy, Aluminium powder, Red mud, Effective thermal conductivity

Now a day’s microelectronics plays an important role in the rapid progress of the electronic and electrical technologies. With increase in integration scale of the microelectronic circuit, more and more heat is produced when the circuit works. As the demands in denser and faster circuits intensify, the heat dissipation in microelectronic application is becoming very crucial. Indeed, the failure to sufficiently conduct heat away from the chip has imposed another engineering constraint in many new product designs\textsuperscript{1}. Polymers have good electrical and mechanical properties, so there is a growing demand for them as packaging materials\textsuperscript{2}. However, commonly used polymers such as epoxy, polyester, polyethylene (PE), polypropylene (PP), polyamide (PA), acrylonitrile-butadiene-styrene (ABS) have low thermal conductivities; because of this they cannot effectively dissipate heat when used in such devices. With improved thermal conductivity, such commonly used polymers would certainly serve as the better alternate option.

The enhancement of thermal conductivity of polymers can be achieved by either molecular orientation\textsuperscript{3} or by adding thermally conductive particles or fibres\textsuperscript{4,5} into it. The usefulness of particulate filled polymer composites has increased because of their versatile applications in science and engineering for technological development. Metals are known for their high thermal conductivity, so they are being widely used as fillers in polymers for improving their thermal conductivity\textsuperscript{6-10}. Apart from metals, some non-metallic fillers like carbon\textsuperscript{11}, graphite\textsuperscript{12}, SiC\textsuperscript{13}, Si₃N₄\textsuperscript{14}, AlN\textsuperscript{15}, Al₂O₃\textsuperscript{16} and ZnO\textsuperscript{17} are also used for improving thermal conductivity of polymers. Among various fillers, aluminium is chosen as filler for the first set of composites. It has been considered to be an ideal candidate due to its very high thermal conductivity, no toxicity, and stable crystal structure and relatively low cost.

It has been seen that pollution is the major problem associated with rapid industrialization, urbanization and rise in the living standards of people. While industrialization is must for uplifting nation’s economy in developing countries, it has also caused the
generation of significant quantities of solid wastes that lead to serious problems relating to environmental pollution. Some industrial waste like fly ash\textsuperscript{18} and copper slag\textsuperscript{19} are proven to be a good replacement of metal particles in the polymer composites because of their thermally conductive behaviour, as fly ash content carbon in it whereas copper is present in its slag. Also being waste product of industries, they are easily available. In view of this, another industrial waste, i.e., red mud which is waste product and generated by alumina production from bauxite by the Bayer’s process can be potential filler for improving thermal conductivity of polymers. Though reinforcement of red mud in polymer is already explored by few researchers, but they studied mainly the mechanical and tribological\textsuperscript{20,21} aspect of it, whereas hardly any work reported on thermal characterization of red mud reinforced polymer composite. In this respect micro sized red mud powder is chosen as another filler material for increasing thermal conductivity of epoxy resin for second set of composites. Apart from experimental findings, there are some theoretical and empirical models for estimating the $k_{\text{eff}}$ of composite materials. The simplest alternative for a two-component composite system would be with the arrangement of materials in either series or parallel with respect to heat flow which gives the $k_{\text{eff}}$ of composite specimen which is based on rule of mixture.

Series conduction model:

$$\frac{1}{k_{\text{eff}}} = \frac{(1 - \phi_f)}{k_p} + \frac{\phi_f}{k_f}$$

... (1)

Parallel conduction model:

$$k_{\text{eff}} = (1 - \phi_f)k_p + \phi_fk_f$$

... (2)

where $k_p$, $k_f$ and $k_{\text{eff}}$ are the conductivity of polymer, filler and composite respectively and $\phi_f$ is the volume fraction of the filler.

A correlation for $k_{\text{eff}}$, employing different assumptions for permeability and field strength for dilute suspension of spherical filler for a homogeneous medium is given by Bruggeman\textsuperscript{23}.

$$1 - \phi_f = \frac{k_{\text{eff}} - k_f}{k_p - k_f} \left( \frac{k_p}{k_{\text{eff}}} \right)^{1/3}$$

... (3)

Maxwell\textsuperscript{24} derived an exact expression for $k_{\text{eff}}$, using potential theory for an infinitely dilute composite of spherical particulates dispersed randomly and devoid of mutual interaction in a homogeneous medium.

$$k_{\text{eff}} = \left( k_f + 2k_p + 2\phi_f \left( k_f - k_p \right) \right) \left( k_f + 2k_p - \phi_f \left( k_f - k_p \right) \right)$$

... (4)

Lewis and Nielsen\textsuperscript{25} gave a semi-theoretical model for a two-phase system which assumes an isotropic particulate reinforcement and also takes into consideration the shape of particle as well as its orientation.

$$k_{\text{eff}} = k_p \left( \frac{1 + A\phi_f}{1 - B\phi_f} \right)$$

... (5)

where $A$ and $B$ are the constants and having a specific value for a particular shape and size of filler particles. Behrens\textsuperscript{26} derived a theoretical model for calculating thermal conductivity for elliptic filaments in a square lattice.

$$k_{\text{eff}} = k_p \left( \frac{(p + 2) + (p - 1)\phi_f}{(p + 2) - (p - 1)\phi_f} \right)$$

... (6)

where $p = \frac{k_f}{k_p}$

The basic aim of present work is to study the physical (density and void content) and thermal (thermal conductivity) property of polymeric material reinforced with particulate filler. The $k_{\text{eff}}$ of a composite material is a complex function of their geometry, the thermal conductivity of the different phases, distribution within the medium, and contact between the particles\textsuperscript{22}. Considerable number of studies that have been carried out experimentally for determination of $k_{\text{eff}}$ of a composite material but analytical determination of $k_{\text{eff}}$ is still remained a less studied area.

In view of this, the present work reports a development of a heat conduction model for particulate filled polymer composite using the law of minimal thermal resistance and equal law of the specific equivalent thermal conductivity. Based on this model, a correlation between the $k_{\text{eff}}$ of the composite and the filler content is proposed. The proposed model is then validated through experimentation conducted in controlled laboratory conditions. Two different filler,
i.e., aluminium and red mud particles are reinforced individually in epoxy matrix to get the required specimen. Also the comparison of \( k_{\text{eff}} \) values obtained from incorporation of two different fillers is reported in this work. For physical characterization, the effect of filler loading on density and void content are determined experimentally and analytically. Few SEM micrographs are also presented to study the shape and size of filler particles and their affinity towards matrix material.

**Development of Theoretical Model**

The three-dimensional view of particulate filled polymer composite cube is shown in Fig. 1a, where elliptical filler particles are uniformly arranged inside the polymer resin whereas Fig. 1b shows the single element which is taken out from composite cube for further study of the heat transfer mechanism, in which a single elliptical particle is situated in the centre of the cube. The assumptions taken while deriving the model are as follows: (i) matrix and filler material both are homogeneous and isotropic, (ii) linear temperature distribution along the direction of heat flow; (iii) thermal contact resistance between the filler and the matrix is negligible, (iv) lamina is free from voids and (v) the density of both matrix and filler material would remain constant throughout the process of composite fabrication.

On the basis of law of minimal thermal resistance and equal law of specific equivalent thermal conductivity, when only conduction mode of heat transfer is considered, and specific equivalent thermal resistance of single element of the composite is considered equal to the total thermal resistance of the composite, then the equivalent thermal conductivity of that single element is considered equal to the total thermal conductivity of the composite, and while considering that it is not necessary to consider the size of the element. Figure 1c shows the front view of element under study having side length \( H \) and a single elliptical particle with minor and major axis of \( h_2/2 \) and \( h_1 \) is located at the centre. The direction of flow of heat is considered from top to bottom at the cubical element.

Figure 1d shows the series model of heat conduction through the unit cell of elliptical particulate filled polymer composite. This element is divided into three parts, Part 1 and part 3 represent pure polymer with thickness \( h_1 \) and \( h_3 \), respectively. Part 2 represents the combination of polymer and particle and its thickness is \( h_2 \). For simplicity thickness of part 1 and part 3 are considered to be equal and is given as \( h_1 = h_3 = (H-h_2)/2 \). The thermal conductivity of individual parts is \( k_1 \), \( k_2 \) and \( k_3 \), respectively. To determine the \( k_{\text{eff}} \) of the whole element, the law of minimum thermal resistance is required to combine the heat resistances of these three parts to get the heat resistance of the complete element and the equal law of the specific thermal conductivity is applied to predict the \( k_{\text{eff}} \) of the complete element. As it has been assumed the linear distribution of temperature, thermal conductivity of each section can be calculated as:

**For part 1 and 3:**

Since there is no filler particle in that region, thermal conductivity of that region will be same as that of polymer matrix, i.e.,

\[
k_1 = k_3 = \int_{h_1} k_p \frac{dy}{h_1} = k_p \quad \ldots (7)
\]

**For part 2:**

Taking an elemental piece with thickness \( dy \), by Fourier’s law of heat conduction, \( k_2 \) is given as:

\[
k_2 = \frac{Q_p + Q_f}{\left( \frac{dT}{dy} \right) A} \quad \ldots (8)
\]

where \( A \) is cross-sectional area of an element under study,

\[
k_2 = \int_{h_2} \frac{(k_p A_p/A + k_f A_f/A)dy}{h_2} = \frac{1}{h_2 A} \left( k_p V_p + k_f V_f \right) \quad \ldots (9)
\]

Where \( k_p \) and \( k_f \) are the intrinsic conductivity of matrix and filler phase respectively, \( A_p \) and \( A_f \) are the cross-sectional areas of matrix and filler phase, respectively.

Similarly thermal conduction resistance of the part 1 and 3:

\[
R_1 = R_3 = \frac{h_1}{k_p A} \quad \ldots (10)
\]

Thermal conduction resistance of the part 2:
Heat transfer is considered as series in the element, the $k_{eff}$ of composites is given by:

$$R_2 = \frac{1}{h_2 A} \left( k_p V_p + k_f V_f \right) A = \frac{h_2^2}{k_p V_p + k_f V_f} \quad \ldots (11)$$

Putting the value of $R_1$, $R_2$ and $R_3$ in the above equation, the equation can be written as

$$k_{eff} = \frac{H}{RA} = \frac{H}{(R_1 + R_2 + R_3)A} \quad \ldots (12)$$

Substituting all required values into Eq. (13) and rearranging it, the final expression is given by:

$$k_{eff} = \frac{1}{k_p} - \frac{1}{k_p} \left( \frac{3\varphi_f}{\pi} \right)^\frac{1}{3} + \frac{3}{\left( k_p \left( \frac{9\pi}{\varphi_f} \right)^\frac{1}{3} + \pi (k_f - k_p) \left( \frac{3\varphi_f}{\pi} \right)^\frac{1}{3} \right)} \quad \ldots (14)$$

Experimental Procedure

Material used

Matrix material

In present investigation, epoxy resin (LY 556) is used as matrix material. Its common name is
Bisphenol-A-Diglycidyl-Ether and it is belonging to the "epoxide" family. Inspite of having low thermal conductivity (0.363 W/m-K) and high CTE (66×10⁻⁶/K), epoxy is chosen because it possesses very low density (1.1 g/cm³) and it is also easily and cheaply available. Epoxy resin is used with its corresponding hardener triethylene tetramine(TETA, HY 951). Epoxy resin and the hardener used for present investigation are procured by Ciba Geigy India Limited.

**Filler materials**

For the first set of polymer composite micro-sized aluminium powder is used as filler material. It is a silvery white metal. Aluminium is considered to be remarkable because of its low density (2.7 g/cm³) and its ability to resist corrosion. Aluminium is primarily chosen because it is highly conducting in nature (205 W/m-K). The aluminium powder used for present investigation is procured from Vedanta, India. For the second set of polymer composite, an industrial waste red mud powder is used as filler material. Red mud is the insoluble product generated after the digestion of bauxite with alkali sodium hydroxide at high temperature and pressure to produce alumina. This process of extraction of alumina is known as Bayer’s process. Its thermal conductivity and density values are 11.7 W/m-K and 3.1 g/cm³, respectively. The red mud powder used for this work is procured from Vedanta, Cochin, India. Sizes of both the filler particles are of approximately 100 microns.

**Composite fabrication**

Conventional hand lay-up technique is used for preparation of polymer composite specimens. For the first set of polymer composite micro-sized aluminium particles are reinforced in epoxy resin. Epoxy resin and the corresponding hardener are mixed in a ratio of 10:1 by weight as per recommendation. Dough is prepared by mixing micro-sized aluminium powder with epoxy resin. A mould is prepared by glass tube coated with uniform thin film of silicone-releasing agent and dough is slowly poured into that mould. The castings are left to cure at room temperature for about 24 h after which the glass mould is broken and the samples are released. Composites of five different compositions with 5 vol%, 10 vol%, 15 vol%, 20 vol% and 25 vol% of fillers are prepared. These fabricated composites are of disc-type specimens (diameter 50 mm and thickness 3 mm). For preparing the second set of composite specimens, industrial waste, micro-sized red mud particles are used as filler material. Following the same procedure, composites of similar five compositions are fabricated again. The different fabricated samples prepared on the basis of volume fraction of particulate filler are shown Table 1.

**Characterization**

**Scanning electron microscopy (SEM)**

Scanning electron microscope (SEM) JEOL JSM-6480LV is used to study the shape and size of the filler particles and the distribution characteristics of such filler particles into the matrix body. The study is done for both particles and their respective composites. All the composite samples are mounted on stubs with silver paste to capture the micrograph of it. Before the micrographs are taken, a thin film of platinum is vacuum-evaporated on composites, for enhance the thermal conductivity of the samples.

**Density measurement**

The densities of all the fabricated composites are measured with the help of Pycnometer. Density determination by pycnometer is considered to be very precise method. Pycnometer works on Archimedes principle. It uses a working liquid with known density, such as water. First the Pycnometer is filled with distilled water. The volume of water filled in Pycnometer is given by:

\[ V = \frac{m_{H_2O}}{\rho_{H_2O}} \]  \hspace{1cm} ... (15)

Where \( m_{H_2O} \) is experimentally measured mass of water (Pycnometer weight subtracted).

After that the Pycnometer is dried, mass of Pycnometer together with inserted composite specimen \( (m_p + m_s) \) is taken. Than mass \( m'_{H_2O}[(m_p + m_s) - (m_c + m_s)] \) is determined by adding water into it. The volume of added water \( V'_{H_2O} \) can be obtained as:

\[ V'_{H_2O} = \frac{m'_{H_2O}}{\rho_{H_2O}} \]  \hspace{1cm} ... (16)

**Table 1 — List of fabricated composites by hand lay-up technique**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Epoxy/Aluminium composites</th>
<th>Epoxy/Red mud composites</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Epoxy + 5 vol% Aluminium particle</td>
<td>Epoxy + 5 vol% Red mud particle</td>
</tr>
<tr>
<td>2</td>
<td>Epoxy + 10 vol% Aluminium particle</td>
<td>Epoxy + 10 vol% Red mud particle</td>
</tr>
<tr>
<td>3</td>
<td>Epoxy + 15 vol% Aluminium particle</td>
<td>Epoxy + 15 vol% Red mud particle</td>
</tr>
<tr>
<td>4</td>
<td>Epoxy + 20 vol% Aluminium particle</td>
<td>Epoxy + 20 vol% Red mud particle</td>
</tr>
<tr>
<td>5</td>
<td>Epoxy + 25 vol% Aluminium particle</td>
<td>Epoxy + 25 vol% Red mud particle</td>
</tr>
</tbody>
</table>
The volume of solid composite \( V_c \) is the difference between the volume of water that fills the empty pycnometer \( V \) and volume \( V'_{H_2O} \)

\[
V_c = V - V'_{H_2O} = \frac{m_{H_2O} - m'_{H_2O}}{\rho_{H_2O}} \quad \cdots (17)
\]

Finally the density “ \( \rho_c \)” can be then calculated as

\[
\rho_c = \frac{m_c}{V_c} \quad \cdots (18)
\]

where \( m_c \) is mass of fabricated composite, \( m_c \) is mass of Pycnometer, \( V_c \) is volume of fabricated composite and \( \rho_c \) is density of fabricated composite.

**Experimental determination of thermal conductivity**

For measuring \( k_{eff} \) of all the fabricated composites, Unitherm™ Model 2022 is used. With the help of this all type polymers, ceramics, composites, glasses, rubbers, some metals and other materials of low-to-medium thermal conductivity can be measured precisely. The tests are in accordance with ASTM E-1530 standard. Disc type specimen of 50 mm diameter and 3 mm thickness with flat surface on both sides were used for the measurement. Material is held under uniform compressive load between two polished surfaces, controlling each sample at a different temperature. The lower surface is part of a calibrated heat flow transducer. Heat flow directs from upper surface through sample to lower surface, establishing axial temperature gradient in stack. On reaching thermal equilibrium, temperature difference across the sample surfaces is assessed along with heat flow transducer output. The sample thickness value is then measured and used to estimate the \( k_{eff} \). The temperature drop through sample is measured using sensors on metal surface layers on either side. In this instrument, transducer measures the value of heat flux \( Q \) and temperature difference between upper and lower plate. Thus, thermal resistance between surfaces can be evaluated. Providing different thickness and known cross-sectional area as input parameters, the samples thermal conductivity can be calculated.

**Results and Discussion**

**Morphology**

The shape and size of the fillers, i.e., aluminium powder and red mud powder are shown in Fig. 2a and 2b,
respectively. It can be seen that the shape of both filler particles, i.e., aluminium and red mud are more or less elliptical in shape. The distribution morphology of fabricated composites, i.e., aluminium/epoxy and red mud/epoxy are shown in Fig. 2c and 2d, respectively. In both sets of composites, filler content is of 20 vol%. From both the figures it can be clearly seen that the distributions of filler particles in epoxy resin are almost uniform. With the increases of filler loading the inter particle distance reduces continuously up to limit that particle start to interfere to each other. For both aluminium and red mud filled composites, it is observed that the both filler particles occupy the space between the epoxy matrixes, resulting in high packing density of fillers in matrix, and thus heat conductive networks are easily formed in epoxy matrix.

Density

Density is a material property which is of prime importance in several weight sensitive applications. Thus, in many such applications polymer composites are found to replace conventional metals and materials primarily for their low densities. The density of a composite depends on the relative proportion of matrix and the reinforcing materials. In the present work, the densities of both the fillers are higher than the pure epoxy.

Pycnometer is used to measure the density of fabricated sets of composites experimentally. The theoretically densities of fabricated composites are calculated by using rule of mixture\(^{13}\):

\[
\rho_c = (1 - \phi_f) \rho_p + \phi_f \rho_f
\]

Where \(\phi_f\) is the volume fraction of filler, \(\rho_c\), \(\rho_f\) and \(\rho_p\) are the density of composite, filler material and matrix material, respectively.

The variation in the density of epoxy matrix composite with filler loading is shown in Figs 3a and 3b. These figures show that with the increase in volume fraction of filler material, the densities of both sets of composites are also increasing. It can also be seen that there are some differences between the experimental and the theoretical densities of fabricated composites. This variation in density is due to the presence of voids and pores in fabricated composites. Table 2 shows the void content in both sets of composites for all the samples. With the increases of filler loading the voids content in composites also increases. These voids significantly affect some of the mechanical properties and even the performance of composites. Higher void contents usually mean lower fatigue resistance, greater susceptibility to water penetration and weathering\(^{28}\).

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Filler content (vol %)</th>
<th>Density (g/cm(^3)) (Epoxy/aluminium)</th>
<th>Voids content (%)</th>
<th>Density (g/cm(^3)) (Epoxy/red mud)</th>
<th>Voids content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>1.18</td>
<td>3.38</td>
<td>1.2</td>
<td>3.33</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>1.26</td>
<td>4.76</td>
<td>1.3</td>
<td>3.33</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>1.34</td>
<td>6.01</td>
<td>1.4</td>
<td>5.71</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>1.42</td>
<td>6.33</td>
<td>1.5</td>
<td>7.33</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>1.5</td>
<td>6.66</td>
<td>1.6</td>
<td>7.5</td>
</tr>
</tbody>
</table>

![Fig. 3 — Effects in density with volume fraction of filler aluminium/epoxy composites](image-url)
Effective thermal conductivity

Figure 4 shows the variation in the value of $k_{\text{eff}}$ when micro-sized aluminium particles is added in epoxy matrix. It shows the comparison between the values obtained from various established theoretical model, experimental values and the proposed model. It is clear from the figure that there is significant increase in the value of $k_{\text{eff}}$ as the content of aluminium particles is increasing. Also it is clear that while none of the established models are predicting the $k_{\text{eff}}$ values correctly, only the model proposed by the authors is in close approximation with the measured values. Though this approximation is only up to 15 vol% after which a sudden jump in the value of measured $k_{\text{eff}}$ observed due to the formation of conductive chain at high filler loading. The vol% at which sudden rise in the value of $k_{\text{eff}}$ observed is called percolation threshold. Similar behaviour is observed in case of epoxy-red mud composite as well, when red mud content increases beyond 20 vol% as shown in Fig. 5. It is clear from both the figures that percolation threshold is not same for all combinations and is changes with either of the

![Fig. 4 — Comparison of effective thermal conductivity of epoxy/aluminium composite: Rule of mixture, Maxwell’s model, Bruggman’s model, proposed model and Experimental values](image1)

![Fig. 5 — Comparison of effective thermal conductivity of epoxy/red mud composite: Rule of mixture, Maxwell’s model, Bruggman model, proposed model and Experimental values](image2)
filler, matrix or both. The difference in the value of percolation threshold is because of the difference in the value of intrinsic thermal conductivity of fillers and their ability to form chain.

Table 3 represents the variation between theoretical and experimental values of fabricated composite specimens along with their associated errors. From the table it is clear that the differences between the experimental and theoretical values are well within the range of 10% up to percolation threshold. It is also interesting to note that with addition of 25 vol% of aluminium particles, $k_{\text{eff}}$ of epoxy increases to 262%, i.e., 1.317 W/mK whereas same volume fraction of red mud increases the $k_{\text{eff}}$ of epoxy by 203%, i.e., 1.102 W/mK. It can be seen that though the difference between the intrinsic thermal conductivity of aluminium and red mud is huge but when they are reinforced in epoxy, the difference in $k_{\text{eff}}$ of their composites is not much as it is explained by Bigg\(^29\) that when the thermal conductivity of filler is 100 times more than that of matrix, there is not much increase in the value of $k_{\text{eff}}$ is observed. So it can be seen that red mud, an industrial waste can replace the costly aluminium particles.

## Conclusions

Based on the experimental and analytical work reported here, it can be concluded that:

(i) Both sets of polymer composites, i.e., epoxy/aluminium and epoxy/red mud composites can be successfully fabricated by simply hand lay-up technique.

(ii) The proposed mathematical model is predicting the $k_{\text{eff}}$ values of both sets of fabricated composites precisely up to percolation threshold.

(iii) An improvement of about 262% in the value of thermal conductivity is recorded with addition of 25 vol% of aluminium filler in epoxy resin whereas when filler material is red mud it is noticed that $k_{\text{eff}}$ increases 203% that of neat epoxy.

(iv) From the SEM images it is clear that particles are more or less elliptical in shape and are uniformly distributed in the matrix body.

(v) There is large difference between the intrinsic thermal conductivity of aluminium and red mud powder, but it can be seen that there is only slight difference between $k_{\text{eff}}$ of their composites. On that basis it can be said that aluminium powder can be replaced by an industrial waste, i.e., red mud.

(vi) These above fabricated composites can find its potential applications in various microelectronics component like printed circuit board, heat sink, packaging substrate etc.

## References


### Table 3 — Theoretical and experimental value of $k_{\text{eff}}$ of composites with error percentage

<table>
<thead>
<tr>
<th>Filler content (vol%)</th>
<th>Effective thermal conductivity (W/m-K)</th>
<th>Difference (%)</th>
<th>Effective thermal conductivity (W/m-K)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoretical</td>
<td>Experimental</td>
<td></td>
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<tr>
<td>5</td>
<td>0.5655</td>
<td>0.525</td>
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<tr>
<td>10</td>
<td>0.6641</td>
<td>0.648</td>
<td>2.48</td>
<td></td>
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<tr>
<td>15</td>
<td>0.7562</td>
<td>0.732</td>
<td>3.30</td>
<td></td>
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<tr>
<td>20</td>
<td>0.85</td>
<td>1.232</td>
<td>31.00</td>
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<tr>
<td>25</td>
<td>0.9493</td>
<td>1.317</td>
<td>27.91</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Epoxy/aluminium composite)</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.5144</td>
<td>0.493</td>
<td>4.34</td>
<td></td>
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<td>10</td>
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<td>15</td>
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<td>6.64</td>
<td></td>
</tr>
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<td>20</td>
<td>0.7678</td>
<td>0.738</td>
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<td>(Epoxy/red mud composite)</td>
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