CHAPTER 4

STUDIES ON THE CHARACTERISTICS OF EPOXY GRANITE WITH VARYING RESIN CONTENT

4.1 INTRODUCTION

In the previous chapter, the selection of aggregate and resin for the polymer concrete mixture and a processing technique for fabrication were discussed. The properties of composite materials depend on the following variables:

a) properties of the constituents

b) shape, size and size distribution of the aggregate/filler

c) morphology generated in the system

d) nature of the inter-phase between the components which depend strongly on their interactions, that is, formation of adhesive bonds.

Thus, a wide range of properties may be obtained with the composites very often by alteration of the morphological and inter-phase properties.
In section 1.8, a brief discussion of previous studies undertaken by researchers, using polymer concrete mixture has been done. It was observed that, the properties of the polymer concrete vary with the composition of ingredients used in the mixture. However, no significant research was found to have studied the mechanical and thermal characteristics together, by varying the composition of ingredients in polymer concrete material, to arrive at a better composition of ingredients. The aim of current investigation was to experimentally investigate the effect of aggregate-resin mix composition on mechanical and thermal characteristics of the epoxy granite developed.

The epoxy granite composites were developed by varying the epoxy resin content in the mixture from 10% to 18% by weight. The compositions of test specimens were evaluated from the mechanical and thermal characteristics exhibited by them.

4.2 METHODOLOGY

Test specimens with varying epoxy content in the mixture from 10% to 18% by weight were fabricated and used to study the characteristics. The mechanical characteristics such as tensile strength, Young’s modulus and compressive strength and the thermal characteristic, thermal conductivity, were determined experimentally for the test specimens. The relatively best composition was arrived at, by investigating the characteristics of the test specimens.

A Scanning Electron Microscope (SEM) analysis was done to study the structure formed by the ingredients in the specimen prepared. The micrographs obtained for the samples, with varying resin content from 10% to 18% by weight was used to analyse the characteristics exhibited by the test specimens.
The characteristics obtained for the epoxy granite material were compared with commercially available materials to arrive at the conclusions. The methodology followed in this study is shown in Figure 4.1.

![Methodology for determination of characteristics](image)

**Figure 4.1 Methodology for determination of characteristics**
4.3 FABRICATION OF TEST SPECIMEN

The tensile and the compressive test specimens were fabricated using mineral cast techniques. The preparation of the aggregate and resin mixture composition used for fabrication has been explained in chapter 3, section 3.3. Wooden moulds were prepared using 6mm thick plywood. Wax was applied on the inner sides of the mould for easy removal of specimen after curing. The specimens were taken out from the mould after 24 hours and were subjected to curing for 21 days before testing.

The resin content in the mixture used was varied between 10% and 18% by weight, in interval of 2%, to study its effect on the properties measured. Three specimens in each composition (a total of 5x3=15 specimens) were fabricated to test repeatability.

4.3.1 Test Specimen for Tensile Test

For conducting the tensile test, a dog bone shape test specimen having dimensions, 60x60x18 mm in the grip and 150x50x18 mm in the test area, was prepared as per ASTM D 3039/D 3039M – 00 standards. The grip part was knurled to obtain a rough surface, to avoid slippage in the grip portion of the test specimen while conducting experiments.

The dimensional details of the specimen and a photograph of the specimen fabricated for conducting tensile test are shown in Figure 4.2(a) and (b) respectively.
4.3.2 Test Specimen for Compressive Test

This work attempts to find the feasibility of using epoxy-granite material in fabricating machine tool structures like the lathe bed, discussed in the next chapter. For a lathe bed, considering most of the structural components are built on it, compression strength is an important characteristic to be analysed.

For conducting compression tests cubical test specimens of size 75x75x75 mm were prepared as per BS 1881 part 116; ASTM C109 standards. The top part, about 20% of the total height of the specimen was filled with fine particles having size less than 0.5mm and up to 140µm to match with commercially available epoxy granite structures. This was done to
simulate the top surface of a lathe bed, where a good surface finish is required to accommodate the movable parts like the tool post and tail stock.

The bottom part was filled with coarse particles, medium particles and fine particles taken in the ratio 50:25:25, so as offer good strength and support to the structure.

A sketch showing the arrangement of particles in the test specimen and a photograph of the specimen fabricated are shown in Figure 4.3 (a) and (b) respectively.

To analyse the characteristics of the material, three specimens in each composition, obtained by varying the resin content in the mixture were prepared.

Wooden patterns were fabricated using 6mm thick plywood to prepare the moulds. The granite particles crushed into required sizes, as explained in section 3.4.1, in the previous chapter. The granite particles were thoroughly cleaned in water, to remove any foreign particles in it. The clean granite particles were then dried in sun light to remove the traces of water content. This was done to obtain proper binding of granite particles with the epoxy resin.

The granite particle mixture and the resin-hardener mixture were mixed thoroughly. A glass rod was used for mixing the ingredients. The mixture was then poured into the wooden pattern prepared.
a) Sketch showing particle arrangement in compression test specimen

b) Fabricated epoxy granite test specimen with 12% epoxy resin content in the mixture and subjected to compression test.

Figure 4.3 Epoxy-granite specimen for compressive test

The wooden mould held firmly in a shaker was vibrated continuously, while pouring the mixture into it. The shaker, vibrating at 40 Hz, with acceleration 3G is shown in Figure 4.4. This was done to remove the gases entrapped between the particles and for strong binding of particles without any void. The wooden mould was opened after 24 hours. The specimens were cured in atmospheric conditions for 21 days.
4.4 EXPERIMENTAL SETUP

The experimental test set up used for conducting tensile test and compression test are discussed in this section.

4.4.1 Tensile Test

An electronic type, TUE-CN-100G, Universal Testing Machine (UTM) was used to conduct the tensile test. The experimental set up is shown in Figure 4.5. The load and elongation for the test specimen subjected to tension were obtained through a digital reader (FIE make, UTE 9301 series) connected to the UTM.
Figure 4.5 Universal Testing Machine (tensile test)

The test specimen was firmly fixed between the upper and middle cross heads. The tensile load was applied hydraulically by operating the valves connected to the cross heads. The tensile load in the specimen and the elongation were noted down using a digital reader attached to the machine using micro-processor attachments.

The nominal stress and nominal strain were calculated using the equations,

\[ \sigma_{\text{nom}} = \frac{P}{A_0} \] (4.1)

where \( P \) = Load carried by the specimen at any moment during the specimen deformation (N) and \( A_0 \) = Original cross sectional area of the specimen (m\(^2\)).
Nominal strain, \( C_{\text{nom}} = \frac{L}{L_0} \)  \hfill (4.2)

where, \( L \) = deformation or change in length of specimen at any moment and \( L_0 \) = Original length between the grips.

### 4.4.2 Compressive Test

A conventional compression testing machine shown in Figure 4.6 was used for conducting the compression test. The test specimen prepared was placed between the compression plates and the load was applied hydraulically.

![Compression testing machine](image.png)

**Figure 4.6 Compression testing machine**

The load corresponding to the visible break in the test specimen was noted down from the dial indicator. This load was used to obtain the compressive strength of the test specimen.
4.5 RESULTS AND DISCUSSIONS

The tensile strength, Young’s modulus and compressive strength were obtained for the test specimens fabricated. A brief analysis of the characteristics were made and discussed in this section.

4.5.1 Tensile Test

A direct tensile test was carried out for the mineral cast epoxy granite structure. The specimens with different mixture content and subjected to tensile test are shown in Figure A 2.1 in Appendix 2. The tensile test was performed by adding the load gradually, such that, the system essentially remains at equilibrium at any given moment so that, static or quasi-static conditions were maintained.

With increase in deformation, the area of the specimen changes and it attains new equilibrium conditions. In order to obtain a valid comparison between the specimens, the tests were carried out at the same atmospheric conditions. The failure in test specimen with 12% resin content in the mixture and subjected to tensile test is shown in Figure 4.7.

Figure 4.7 Failure in specimen subjected to tensile test with 12% resin content in the mixture

The tensile strength is the maximum tensile stress supported by the specimen during the tension test. The tensile stress is the tensile load carried
by the specimen divided by the original cross sectional area of the specimen within gauge limits.

The stress strain curves for the five specimens fabricated with different composition of mixture used in this analysis are shown in Figure 4.8 (a) to (e).

(a) With 10% epoxy resin content  
(b) With 12% epoxy resin content  
(c) With 14% epoxy resin content  
(d) With 16% epoxy resin content

Figure 4.8 (Continued)
(e) With 18% epoxy resin content

Figure 4.8  Stress strain curves for test specimens with varying epoxy resin content in the mixture

The stress-strain curves obtained indicates that polymer composites have a varied range of properties, depending on the base polymer and the type and content of the aggregates. In this case, the variation in curves may be due to the varying composition of aggregate-resin content in the mixture, adhesion between the ingredients or due to agglomeration of aggregates.

The average tensile strength obtained for the three specimens, in each category with varying epoxy resin content in the mixture is shown in Figure 4.9.
Figure 4.9  Tensile strength for Epoxy Granite specimens with varying resin content in the mixture

From the results, it was observed that, the tensile strength was better with 12% and 14% epoxy content in the mixture. This could be due to perfect adhesion of particles. With 10% epoxy content in the mixture the tensile strength was less than the mixture with 12% and 14% epoxy content. This may be due to weak bonding of particles, due to insufficient epoxy content in the mixture (Kim et al, 1995).

With 16% and 18% resin content, the tensile strength was observed to be less compared to the composition with lesser epoxy content in the mixture. Maiti et al (1995) observed that, a larger volume of epoxy resin around the larger aggregate particles will be confronting the stress concentration, leading to bigger voids when subjected to tensile loading.
According to Bouzakis (2008), the tensile strength decreases with increase in epoxy resin thickness from 0.2 mm to 0.9 mm due to the increase in stress concentration at the interface of materials. Hence, it can be concluded that, with larger volume of epoxy content in the composition, the voids in the structure expand quickly due to tensile load, resulting in lesser tensile strength.

To study the internal structural detail of the specimen, the Scanning Electron Microscope (SEM) analysis was carried out as discussed in the following section.

4.5.2 SEM Analysis

For conducting the SEM analysis, cubical samples of side 5 mm were taken from the fabricated test specimen. The samples were dried with lint cloth to remove the dust and then the samples were fixed into the holder using wax. The sample was kept inside a vacuum chamber. The photomicrographs were obtained with required amplifications and the files were stored in the computer attached.

The specimen surfaces were examined using an optical microscope Zeiss sigma VP (Schottky-Emitter) make, as shown in Figure 4.10 with a system for capturing images. SEM analysis was carried out from 300µm to 10µm level to study the grain structure of the epoxy granite test samples with varying resin content between 10-18%.
The photographs showing the constituents structural formation for varying epoxy resin content between 10% and 18% are shown in Figure 4.11 a-e. From the microscopic view of the samples, it was observed that, the particles were angular in nature. Also, the photographs revealed that with 10% by weight of resin in the mixture, the particles were not attached firmly to the matrix. This could be due to a thin resin layer above the granite particles, which reduces interfacial bonding strength between the particles and resin. With 12% to 14% by weight of resin in the mixture, the particles form a homogeneous and denser structure, the particles were found to be attached firmly to the matrix.

By increasing the epoxy resin content in the mixture from 16 % by weight to 18% by weight of resin content, the aggregate particles were less densely packed and the resin forms a puddle, that is, a thick layer of resin was found between the particles. Also, the granite particles were found to be well separated by the resin.
a) With 10% epoxy content (Particles not well bonded to resin)

b) With 12% epoxy content (Homogeneous, dense particles attached firmly to resin)

c) With 14% epoxy content (Homogeneous, dense particles)

d) With 16% epoxy content (Less densely packed particles)

e) With 18% epoxy content (Resin forms a puddle)

Figure 4.11 SEM photographs for epoxy granite with varying epoxy content in the mixture.
This increase in thickness of the epoxy content results in poor load transfer between aggregate particles with application of load. This is because, with the increase in tensile force, the ductility deterioration for the resin content occurs leading to abrupt failure of the specimen. Also, researchers Bouzakis et al, (2008) and Maiti et al (1995) had observed and reported a similar trend in epoxy concrete structures. Hence, it is concluded that with the increase in thickness of resin content the tensile strength decreases.

Hence, a higher concentration of resin content in the mixture is not preferable. Moreover, epoxy resin was the costliest (Rs.500/- per litre) ingredient used in the mixture. Hence, a mixture combination that gives desired properties with a lesser usage of resin was preferred.

4.5.3 Young’s Modulus

Young’s modulus is an important property of a structural material, which gives an indication of the stiffness characteristic of the structure made using the material. The stress-strain curve plotted for materials with varying epoxy content in the mixture was given in Figure 4.8.

The Young’s modulus was obtained from the slope of the stress-strain graph in the elastic range. This property is relatively invariant for small changes in molecular weight, presence of flaws or impurities incorporated during fabrication process, because it is a function of crystallization bonding forces.

The incorporation of aggregate into the polymer matrix stiffens or strengthens the later in a complex manner. The polymer molecular mobility and sequential deformability is impeded by the particles which imposes a mechanical restraint. The degree of this restraint depends on the matrix, particular spacing along with its size, shape, volume fraction as well as the
interfacial interactive force between the ingredients. The Young’s modulus for the epoxy granite for varying resin content in the mixture is shown in Figure 4.12.

![Bar graph showing Young's modulus variation](image)

**Figure 4.12  Young’s modulus variation with varying resin content in the mixture**

It was observed that the Young’s modulus increases with increase in percentage of epoxy content in the mixture from 10% to 14% and decreases with 14-18% of epoxy content in the mixture. This indicates that the structure with 12% -14% of epoxy content in the mixture possess high stiffness and damping characteristics compared to other combinations. The increase in Young’s modulus can be attributed to the size of fine particles, and its concentration used in the mixture. The fine particles occupy the space between larger particles filling the voids. A high concentration of granite particles in the mixture provides maximum load transfer through the material thus giving it a high Young’s modulus and strength.
4.5.4 Compression Test

The specimens with different mixture content and subjected to compression test are shown in Figure A2.2 in Appendix 2. The failures in specimens observed during compression are shown through Figures A 2.3 to A 2.7 in Appendix 2. The compressive strength for the specimens fabricated is shown in Figure 4.13. The average values obtained for the three specimens in each composition was noted down as the compressive strength for that composition.

![Figure 4.13 Compression strength for test specimens with varying epoxy content in the mixture](image)

It was observed that the compressive strength is high when the aggregate content is more in the composition. However, with 10% epoxy content in the mixture, the strength is less compared to 12% epoxy content in the mixture. This could be due to weak binding of granite particles with the epoxy resin, leading to failure with the application of load. Kim et al (1995)
used pebble as aggregate and resin weight in the ratio 5-10% and observed that the lesser epoxy content in the mixture gives lesser compressive strength. Sridhar et al (2011) conducted tests using dolerite as aggregate and epoxy resin as binder and observed that the compressive strength decreases with increase in epoxy content in the mixture.

With a higher percentage of epoxy content in the mixture, the aggregate content decreases, resulting in more porous structure. The pores will get filled by the soft epoxy resin material. Hence the adhesive bond strength given by the epoxy to the granite particles are irregular leading to a non-linear stress strain transformations. This could be the reason for reduced compressive strength with higher epoxy content.

Again, from the structural micrographs obtained from SEM analysis it was observed that, with higher percentage of resin content in the mixture, the resin forms a puddle. The lesser aggregate content in the mixture leads to lesser stiffness resulting in relatively quick failure of the test specimen.

4.6 COMPARISON OF MECHANICAL CHARACTERISTICS

The summary of mechanical characteristics determined for the epoxy granite developed with 12% by weight of epoxy resin and 88% of aggregate in the mixture was compared with some commercially available epoxy-granite materials such as harcrete, anocast and zanite. The characteristic values are given in Table 4.1.
Table 4.1 Mechanical Characteristics for epoxy granite

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition</th>
<th>Tensile strength (MPa)</th>
<th>Compressive strength (MPa)</th>
<th>Young’s Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developed</td>
<td>12% epoxy and 88% granite</td>
<td>12.9</td>
<td>114</td>
<td>31</td>
</tr>
<tr>
<td>Anocast</td>
<td>8% epoxy and 92% silica</td>
<td>15.2</td>
<td>110-117</td>
<td>36</td>
</tr>
<tr>
<td>Zanite</td>
<td>7% epoxy and 93% granite</td>
<td>14.5</td>
<td>137</td>
<td>31</td>
</tr>
<tr>
<td>Harcrete</td>
<td>7% epoxy and 93% granite</td>
<td>15.8</td>
<td>108</td>
<td>37</td>
</tr>
</tbody>
</table>

It was observed that the mechanical characteristics obtained for the developed epoxy granite were close to the values available for commercially available similar materials. The compressive strength was observed to be better than harcrete, in the range of anocast and smaller than the zanite.

The thermal characteristic, thermal conductivity was analysed in the following section for varying resin content in the mixture to reach a better conclusion in the selection of aggregate-resin mixture for fabricating the epoxy granite lathe bed.

4.7 EVALUATION OF EFFECTIVE THERMAL CONDUCTIVITY

In the epoxy granite composite which has two ingredients, effective thermal conductivity is an important physical property that had to be determined. Techniques used to determine the effective thermal conductivities can be classified as either steady state methods or transient methods.
In the steady state technique, a steady temperature gradient builds up over a known thickness of the sample. The major disadvantage of this technique is that it is a time consuming technique and requires a large sample size.

This study was done to determine the effective thermal conductivity of epoxy-granite material using the Transient Plane Source (TPS) method, to study the effect of varying the volume fraction of epoxy content in the mixture on the thermal conductivity of the epoxy granite material.

**4.8 FABRICATION OF TEST SPECIMEN**

The test specimen consists of two cylindrical blocks of radius 35mm and thickness 12.8mm as shown in Figure 4.14. The densities of the samples were taken as $2300 \pm 4\%$ kg/m$^3$.

To reduce the contact errors of thermocouple with unwanted surfaces, a 2mm sheath was placed at the centre of the bottom block. The thermocouple was inserted through the sheath such that its tip just touches the center of the heater.

![Figure 4.14 Test specimen (with 16% epoxy resin and 84% aggregate in the mixture) for measuring effective thermal conductivity using TPS method.](image-url)
4.9 EXPERIMENTAL SET UP

A schematic diagram and a photograph of experimental setup used are shown in Figure 4.15(a) and Figure 4.15 (b) respectively. This setup developed by Senthilkumar et al (2010) and available in the fluid machinery lab of the mechanical engineering department was used to find out the thermal conductivity of the samples using TPS method.

Figure 4.15 (a) Schematic diagram for experimental set up: TPS Method

Figure 4.15 (b) Experimental set up: TPS Method
The components of the set up consist of,

- A sample container consisting of two cylindrical wooden blocks which holds the test specimens. The inner surfaces of the containers are well insulated with glass wool to avoid lateral heat transfer losses.

- A heater made up of 10μm nickel metal wire wound into double spiral shape as shown in Figure 4.16 and well supported by a polymer film called ‘Kapton’ was used. Kapton protects the shape of the coil and gives good electrical insulation and mechanical strength to the heating coil.

![Figure 4.16  Heater wire with Kapton](image)

- An iron-constantan metallic, J-Type thermocouple (0 to 700 °C) was used to measure the temperature. The thermocouple was fixed firmly and its tip touches the mid of the spiral heater through a small hole having 2mm diameter, at the center of the bottom sample. A sheath was provided between the thermocouple and the specimen to avoid any contact errors between them.
- The thermocouple is interfaced with a computer through an SCXI 1303 data acquisition (DAQ) system which records the data on a computer directly with minimum error.

- LabVIEW software installed in the computer is programmed to collect the temperature data from the thermocouple and stores the data every 30 seconds.

- A PSD 3304 DC power supply was used to provide heat input to the heater.

- Using the time and temperature data collected, a graph was plotted between $\ln$ (time) vs Temperature. Using the slope of the curve plotted, the effective thermal conductivity was determined.

A wooden cylindrical container with its inner surface well insulated with glass wool to avoid any heat loss to the surroundings, was used to hold the specimen. The heater sandwiched between the specimens was firmly fixed between the wooden containers.

The thermocouple connected to a Data acquisition (DAQ) card was inserted through a sheath in the bottom specimen and placed firmly such that it touches the center point of the heater. The DAQ card receives signals from the thermocouple and it was processed by a computer with LabVIEW 8.5 software. The LabVIEW programme developed for measuring thermal conductivity is given in Appendix A 1.1.

A DC Power source was used to supply power to the heater. The time dependent temperature rise was noted down for every 30 seconds in a computer with LabVIEW programme.
4.10 RESULTS AND DISCUSSIONS

The \( \ln (t) \) vs. \( T \) graph was plotted with the time \( (t) \) - temperature \( (T) \) values obtained for every thirty seconds using the LabVIEW programme. The plotted graph for the specimen with 12\% epoxy resin content in the mixture is shown in Figure 4.17.

\[ \ln (t) \text{ vs. } T \]

Figure 4.17 The initial lag error and axial error regions

The graph is an ‘S’ shaped curve with initial lag error and axial error regions. The initial lag error occurs due to the lag in temperature response due to heat transfer coefficient between the surface of heat source and testing material. The axial error occurs at higher temperatures at which the heat wave was absorbed or reflected by the testing material in axial direction. The slope of the curve, obtained after neglecting these error regions, was used to determine the thermal conductivity of the material.

Trial and error method reported by Al-Ajlan (2006) and Bentz (2007) was adopted to determine the slope corresponding to the selected
temperature, such that the values of thermal conductivity calculated from the slope was repeated within 2% error limit. According to the transient plane source theory discussed in section 1.8.1, chapter 1, the slope of the graph is given by Equation 4.3

\[
Slope = \left[ \frac{P_0}{\pi^{3/2} \cdot a \cdot k_{eff}} \right]
\]

Knowing the amount of heat supplied and the slope of the graph, the effective thermal conductivity of the test material was determined. The experiment was repeated three times and the average value of thermal conductivity calculated. The experiment was repeated with other specimens prepared. Thermal conductivity obtained for specimens with varying resin content with varying temperature is shown in Figure 4.18.

Figure 4.18 Variation of effective thermal conductivity with temperature (Power input:1W)
The thermal conductivity obtained at temperature 27°C, for the specimens with varying epoxy content (% x) in the mixture ranging from 10-24%, is tabulated in Table 4.2 and plotted in Figure 4.19.

Table 4.2 Effective thermal conductivity obtained from experiments

<table>
<thead>
<tr>
<th>Epoxy content in mixture</th>
<th>Experimental thermal conductivity, k, W/mK</th>
<th>Average effective thermal conductivity, $k_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_1$</td>
<td>$k_2$</td>
</tr>
<tr>
<td>10%</td>
<td>3.0020</td>
<td>3.1317</td>
</tr>
<tr>
<td>12%</td>
<td>2.4465</td>
<td>2.5475</td>
</tr>
<tr>
<td>14%</td>
<td>2.4548</td>
<td>2.8359</td>
</tr>
<tr>
<td>16%</td>
<td>2.5478</td>
<td>2.6365</td>
</tr>
<tr>
<td>18%</td>
<td>2.5860</td>
<td>2.5368</td>
</tr>
</tbody>
</table>

Figure 4.19 Variation of effective thermal conductivity with varying epoxy resin content in the mixture
It was observed that thermal conductivity decreases with increase in epoxy content in the mixture. Neglecting the effect of size of crushed granite particles on thermal conductivity (Filho et al, 2008), the trend observed could be due to the presence of epoxy resin having very low thermal conductivity (0.363 W/m. K), between the granite particles.

Incropera & Dewitt (2005) had reported that the presence of matter with lesser thermal conductivity between surfaces results in lesser effective thermal conductivity. Hence in this study it is concluded that, the use of epoxy resin for permanent bonding between the particles increases the interfacial resistance between the particles which in turn reduces the heat transfer between the surfaces reducing the effective thermal conductivity.

The effect of the other substances’ presence, such as air or other foreign particles between the aggregates, on thermal conductivity are neglected considering the steps taken during the manufacture of the sample such as 1) thorough cleaning and drying of aggregate particles removing any foreign particles in them and 2) use of a horizontal shaker for proper filling of aggregates of different sizes without any void between particles and removal of air trapped between them increasing the compactness of the specimen prepared.

To validate the results found out experimentally using TPS method, three empirical models, namely the Hashin-Shtrikman (H-S) bounds, Jean Cote model and geometric mean model as given by Bentz (2007) and Cote et al (2011) were used.

The upper and lower H-S bounds for thermal conductivity of two phase material were calculated using Equation (4.4) and (4.5) respectively.
For, \( k_2 \geq k_1 \)

\[
k_i = k_1 + \frac{x_2}{1 + \frac{x_1}{3k_1}}
\]

(4.4)

\[
k_u = k_2 + \frac{x_1}{1 + \frac{x_2}{3k_2}}
\]

(4.5)

where, \( k_i \) and \( k_u \) are the upper and lower H-S bounds for thermal conductivity, \( k_1 \) and \( k_2 \) are the thermal conductivities of epoxy and granite materials respectively with volume fraction of epoxy resin \( x_i \) and granite particles \( x_2 = 1 - x_i \), in the test sample.

The upper and lower bounds of thermal conductivity were calculated by taking thermal conductivity for epoxy as 0.363 W/m.K as per the data given by the manufacturer and for the granite as 3.5 W/m.K. The H-S bounds, \( k_{upper} \) and \( k_{lower} \), for varying concentration of epoxy and the experimental values of thermal conductivity are plotted in Figure 4.20.

It was observed that, the thermal conductivity values obtained experimentally are well within the bounds.

The thermal conductivity values obtained experimentally for the samples were compared with the average values of H-S bounds and the values obtained using the correlation given by Cote et al (2011) given in Equation (4.6) and by applying the geometric mean formula given in Equation (4.7).
where, $k_{2p}$ is the fluid to solid thermal conductivity ratio given by,

$$k_{2p} = 0.29 \left( \frac{15k_f}{k_s} \right)^{\beta}$$

and $k_f$ and $k_s$ are the thermal conductivity of fluid and solid respectively and $\beta$ is the empirical parameter accounting structure effects on thermal conductivity.

$$k = (k_s)^{(1-n)}k_f^n$$

where ‘n’ is the epoxy content in the mixture. The experimental values of thermal conductivities and the values calculated from the models are tabulated in Table 4.3.
Table 4.3  Comparison of effective thermal conductivity obtained from experimental and empirical methods

<table>
<thead>
<tr>
<th>% epoxy content in mixture</th>
<th>HS bounds Ave</th>
<th>Cote., et al Correlation</th>
<th>Geometric Mean</th>
<th>This experimental study.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>2.9522</td>
<td>2.8889</td>
<td>2.9334</td>
<td>2.9594</td>
</tr>
<tr>
<td>12%</td>
<td>2.8328</td>
<td>2.7566</td>
<td>2.8003</td>
<td>2.7964</td>
</tr>
<tr>
<td>14%</td>
<td>2.7206</td>
<td>2.6323</td>
<td>2.6733</td>
<td>2.6911</td>
</tr>
<tr>
<td>16%</td>
<td>2.6148</td>
<td>2.5152</td>
<td>2.5520</td>
<td>2.5391</td>
</tr>
<tr>
<td>18%</td>
<td>2.5147</td>
<td>2.4047</td>
<td>2.4362</td>
<td>2.4340</td>
</tr>
</tbody>
</table>

A graphical comparison of experimental values with the values calculated using correlations, is shown in Figure 4.21.

Figure 4.21 Comparison of effective thermal conductivities
It was observed that, the thermal conductivity values obtained from the experimental study were very close to the values obtained by using correlations given by Cote et al (2011) and geometric mean formula. The experimental values were very close to H-S bound average values at lower temperatures and vary within ±3% error limit at higher temperatures. This indicates the suitability of TPS method in the measurement of thermal conductivity for epoxy granite materials and in general for any two phase composite material.

The thermal conductivity values for the mineral cast epoxy granite material was found to be in the range of 2-3 W/mK, which is twenty-five times lesser than that of a conventional cast iron material, having a thermal conductivity value of 50 W/mK. This shows that, the epoxy granite material will take a longer time to transport the heat generated in the structure. The heat that may get stored in the structure can be reduced by selecting a mixture with lesser epoxy content, preferably in the range of 12-14% which maximizes the thermal conductivity without sacrificing its mechanical properties.

The lower value of thermal conductivity obtained from experimental methods for the developed material (2.1021 W/mK) was compared with some of the manufacturers producing similar material and shown in Figure 4.22. The thermal conductivity for the developed material was found to be closer to Anocast’s Silica filled epoxy polymer composite (1.63 W/mK) with 92% silica and 8% epoxy (www.matweb.com), it is about 11.6 times smaller than Anocast’s anorad (24.4 W/mK) (www.matweb.com) and about nine times smaller than Zanite (19.1 W/mK) (www.zanite.com).
CONCLUSIONS

In this work, the mechanical characteristics of mineral cast structure were evaluated for varying the epoxy resin content in the mixture from 10% to 18% maintaining the density of the mixture constant. It is detected that 10% epoxy content in the mixture affects the binding characteristics of the aggregate with the resin affecting the mechanical characteristics. Higher the epoxy content in the mixture, between 16-18%, results in formation of puddles of resin above the aggregate affecting the characteristics. Also, with higher percentage of epoxy resin, for the same density, the aggregate material in the mixture decreases. This affects strength characteristics. Hence, 12-14% of epoxy resin in the mixture was observed to offer optimum mechanical characteristics to the structure. Considering the high cost of the epoxy resin, its usage in the mixture should be kept minimum, hence a material with 12% by weight of epoxy resin-hardener mixture and 88% aggregate was observed to provide required mechanical characteristic at an optimum cost.
Comparing the properties of the developed epoxy granite with the commercially available similar materials it is observed that, the compressive strength was better than harcrete and the epoxy granite composite developed by Filho et al, in the range of anocast and smaller than the zanite.

Experiments were carried out to determine the effective thermal conductivity of a mineral cast epoxy granite material using transient plane source techniques and to study the variation in thermal conductivity with varying volume fraction of epoxy content in the mixture. The measurement of thermal conductivity for eight samples with epoxy content varying in the range 10-18% has been presented. A reduction in effective thermal conductivity was observed with increasing epoxy resin content in the mixture due to the presence of an interfacial material having low thermal conductivity (epoxy resin), which increases the interfacial resistance between the aggregate materials (granite particles).

The effective thermal conductivity of the epoxy granite is observed to be in the range of 2-3 W/mK, which is twenty five times smaller compared to conventional cast iron material for which the thermal conductivity is about 50 W/mK. As a result, the supporting structure in a machine tool, made of epoxy granite material will reduce the thermal energy transport through it to other machine parts. However, an effective cooling method is required to carry away the heat stored in the supporting structure.

A mixture with lesser epoxy content in the range 12-14% was found to maximize the thermal conductivity. By comparing the experimental thermal conductivity values with, empirical models such as H-S bounds, Cote et al and geometric mean correlations; it is observed that the experimental values are well within the range. TPS method was found to be quick and reliable technique for measuring thermal conductivity of composite materials.
From the mechanical and thermal characteristics evaluated, it is observed that, the epoxy granite with 12% epoxy content in the mixture is suitable for the fabrication of machine tool structures. Based on this analysis, a lathe bed having same stiffness as that of a micro-lathe bed was fabricated using epoxy granite. The characteristics such as damping ratio, dimensional stability, surface finish and wear were analysed and discussed in the next chapter.