

# Theoretical Prediction and Experimental Validation of Thermal Conductivity in Glass Fabric Reinforced Epoxy Hybrid Composites

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**Abstract:** This research focuses on investigating the thermal properties of hybrid composites comprising glass fabric reinforcement integrated with a combination of micro and nano sized fillers. Glass fabric-reinforced epoxy composites incorporating varying proportions of micro and nano sized fillers ( $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$ ,  $\text{SiC}$ , graphite,  $\text{MoS}_2$ , and cenosphere) were developed using the hand lay-up technique in conjunction with a bagging process. The developed hybrid composites underwent Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC), and Thermal Conductivity (TC) testing to assess their thermal properties. Furthermore, an investigation was conducted to correlate the experimental data with the results obtained from mathematical modelling regarding the effective TC of the hybrid composites. From the study, it was evident that the composite containing 5 wt.% of  $\text{SiC}$  exhibited a glass transition temperature of  $146.16^\circ\text{C}$  and a TC of  $0.52 \text{ W/mK}$ . These hybrid composites demonstrate potential for use in electrical insulation, structural elements in automotive and electronics enclosures, and applications requiring enhanced thermal management in the  $100\text{-}200^\circ\text{C}$  range. The composite containing cenosphere and  $\text{MoS}_2$  exhibited a higher thermal conductivity of  $0.68 \text{ W/mK}$  and 24% increase in thermal conductivity compared to the base composite.

**Keywords:** differential scanning calorimetry; Glass fabric; hybrid fillers; thermal conductivity; thermogravimetric analysis

## 1. Introduction

Polymer composites have found extensive applications in aerospace, automotive, military, and medical device productions owing to their exceptional specific stiffness and strength, significant damping capacity, corrosion resistance, and low thermal expansion characteristics<sup>1-3</sup>. The significance of fibre-reinforced composites includes simplistic fabrication methods, high specific modulus and strength, good resistance to corrosion and fatigue, superior design flexibility, and desirable thermal expansion characteristics.

The versatile characteristics of polymers make them exceptionally well-suited for a broad spectrum of applications spanning critical industries, including aerospace, automotive engineering, telecommunications, construction, electrical infrastructure, energy storage, and various other advanced applications<sup>4,5</sup>. Elevating the volume concentration of reinforcement within a composite has been demonstrated to improve its thermal properties. This augmentation significantly boosts its thermal

conductance, provided that the reinforcement materials are evenly distributed throughout the composite<sup>6</sup>. The properties of fibre-reinforced composites are strongly impacted by the fiber alignment and the type of fabric employed<sup>7</sup>. Glass fabric reinforcements significantly enhance the physical and mechanical properties of the polymer matrix<sup>8-10</sup>.

Epoxy resins are extensively used as polymer matrix in electronics and electrical applications owing to their exceptional mechanical and adhesive properties<sup>11,12</sup>. Owing to their cross-linked structure, they exhibit low thermal and electrical conductivity. The growing range of engineering applications is supported by recent material innovations<sup>13</sup>. In epoxy composites, thermal conductivity is governed by polymer–filler interfacial interactions and the intrinsic properties of the fillers, including their thermal conductivity, surface area, and morphology<sup>14</sup>.

Composites with micron-sized fillers have been widely used over the last few decades for achieving better dielectric, mechanical and thermal properties. However,

due to its relatively larger size, micron filler particles exist closely in a polymer matrix, and the use of micron fillers is always associated with a certain degree of compromise on the polymer composites' properties<sup>15</sup>). The prominent attributes of inorganic fillers that significantly enhance the electrical and thermal properties in hybrid composites include particle size, shape, and the bonding ability between particles and the polymer matrix<sup>16</sup>). In<sup>17</sup>), it was reported that enhanced interactions between epoxy and cenosphere, along with the formation of cross-linked structures, promote increased crystallinity, thereby improving the insulating properties of the composites. The hybrid composite blended with Al<sub>2</sub>O<sub>3</sub> micro and nanofiller particles exhibits improved mechanical and thermal properties than composites with SiO<sub>2</sub><sup>18</sup>).

The usage of customised hybrid fillers in a matrix has been confirmed to be a huge success in enhancing mechanical, thermal, and viscoelastic properties<sup>19</sup>). By incorporating inorganic fillers such as SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and SiC in polymers, it has been possible to attain precise thermal, electrical and mechanical properties, as reported in the literature<sup>20</sup>).

From the state-of-the-art, it is also evident that the most significant drawback of polymer composites is their vulnerability to ageing under thermal loads. The use of hybrid fillers helps to resist thermal ageing to a considerable extent<sup>21</sup>).

The utilisation of an altered polymeric matrix with a combination of hybrid fillers has emerged as a cutting-edge research approach for achieving enhanced stability in mechanical, viscoelastic, and thermal properties, thereby facilitating a broad spectrum of industrial applications<sup>19</sup>). The improved and balanced thermal, mechanical, and electrical properties of polymer composites with nanoscale fillers have resulted in wide-ranging applications in the engineering sector. It is generally observed that only one distinctive property improves significantly, while the others show only minor changes or, in some cases, deterioration due to the incorporation of micron or nanofillers. As a result, hybrid composites are ideal replacements for conventional polymer nanocomposites for multifunctionality. Two polymer matrices, two or more fillers or a mixture of fillers and polymer matrices form hybrid composites<sup>22</sup>). The combination of micron and nanofillers in polymers has opened new possibilities for enhancing the thermal, mechanical, and electrical properties.

The authors<sup>23</sup>) highlighted that the combination of a ceramic filler (SiC) with a metallic filler (copper) leverages the high thermal conductivity of copper and the excellent mechanical reinforcement capability of SiC, resulting in composites suitable for thermal management applications. The study<sup>24</sup>) reported that spherical and platelet-shaped fillers tend to form more efficient thermal networks, thereby enhancing heat dissipation. The authors also noted the critical role of filler-matrix interfacial

compatibility in reducing thermal resistance, which is vital for applications in electronics and aerospace sectors. The hybridisation of fillers led to the formation of complementary thermal networks and improved interfacial interactions, which contributed to superior thermal management performance without compromising dielectric strength<sup>25</sup>).

The benefit of reinforcement with a single filler (either micro or nano-sized filler) in a polymer composite may be hard to meet the tough and demanding requirements of different applications. Therefore, the present trends in material technology are focused on the usage of a mixture of micro and nano fillers. The hybrid combination of fillers enables the attainment of multifunctional capabilities with the added benefits of well-balanced thermal, mechanical, and electrical properties. Many research investigations in recent years have focused on improving the multifunctional capability of polymer composites by incorporating micron and nano-sized fillers and optimising their ratios.

Thermal shifts in amorphous and semi-crystalline polymers follow a typical characteristic shown in Figures 1 and 2, respectively. With an increase in temperature, both semi-crystalline and amorphous polymers undergo the glass transition (T<sub>g</sub>) phase. Amorphous polymers do not have any other phase transitions, but semi-crystalline polymers undergo crystallisation and melting as shown in Figure 1.

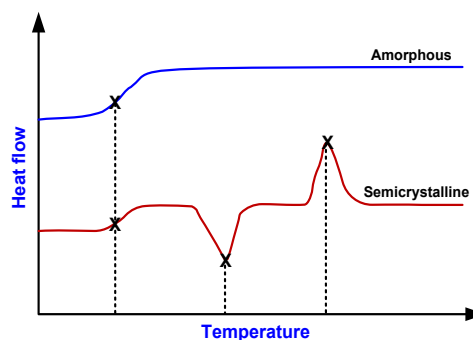


Fig. 1: Thermal transitions in amorphous and semi-crystalline polymers<sup>26</sup>)

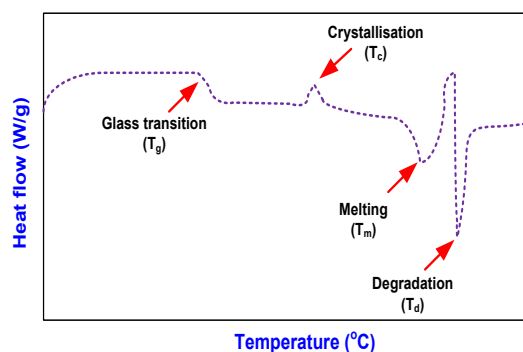


Fig. 2: Thermal transitions in semi-crystalline material obtained from DSC thermograms<sup>26</sup>)

The main advantage of DSC is the modest requirement of sample size, which is of the order of milligrams. Further, it provides quantifiable data on the complete reaction kinetics involved rapidly, and the ease of handling the instrument is an added advantage. Besides, it gives measurements of thermal transition, namely the glass transition temperature ( $T_g$ ).

From the state-of-the-art, it is manifest that hybrid composites have certain advantages over conventional micron filler-based composites as well as nanocomposites. However, the utilisation of hybrid fillers incorporating both micron and nano dimensions remains limited in current research and application contexts. The lack of investigation and implementation is notable within the field of materials science and nanotechnology, where studies focusing on such hybrid filler systems are relatively less. Hence, detailed investigations were carried out to understand their effect on thermal properties, which are crucial for extending the usage of hybrid composites for both electrical and structural applications.

## 2. Experimental method

This section provides detailed information regarding the materials utilised and the fabrication method employed.

### 2.1. Materials

Table 1 presents the detailed specifications of the matrix, reinforcement, and filler particles employed in the proposed fabrication method. The nanofillers comprising MoS<sub>2</sub> and graphite are procured from local sources.

### 2.2. Fabrication process

The method proposed entails employing the hand lay-up technique with bagging, followed by compression moulding, to produce polymer hybrid composites, as elaborated in reference<sup>27</sup>. Table 2 furnishes specifics regarding the fabricated samples and their corresponding identification for result discussions.

The selected filler loadings of 1 wt.% nanofillers and 4-5 wt.% microfillers were based on prior optimisation studies<sup>27, 28</sup>, which reported this range to achieve balanced

**Table 1:** Specifications of the materials employed in the hybrid composites.

Materials	Source	Density (g/cm <sup>3</sup> )
ECR glass fabric	Owens Corning (India)	2.66
Epoxy (MY740)	Huntsman (USA)	1.16
Alumina (Al <sub>2</sub> O <sub>3</sub> )	Sigma Aldrich (India)	2.62
Silica (SiO <sub>2</sub> )		4.0
Silicon Carbide (SiC)		3.1
Graphite		2.6
Molybdenum disulfide (MoS <sub>2</sub> )		5.06
Cenosphere (CS)	Thermal Power Station	2.23

**Table 2:** Composition of the hybrid composites

Sample	Materials used (Wt. %)		
	Epoxy	Nano Filler	Micron Filler
GE	40	--	--
GEA	35	1	4
GES	35	1	4
GESiC	30	1	4
GEC5	35	--	5
GEC10	30	--	10
GECM	30	1 (MoS <sub>2</sub> )	5 (CS) + 4 (MoS <sub>2</sub> )
GEG	35	1	4

(60 Wt.% of ECR glass fabric was used for all the samples)

dispersion, prevent agglomeration of nanoparticles, and maintain mechanical integrity while achieving noticeable thermal property enhancement.

## 3. Measurement techniques

In this section, experimental techniques and procedures adopted for investigating the thermal characteristics of fabricated hybrid composites are discussed.

### 3.1. Differential scanning calorimetry

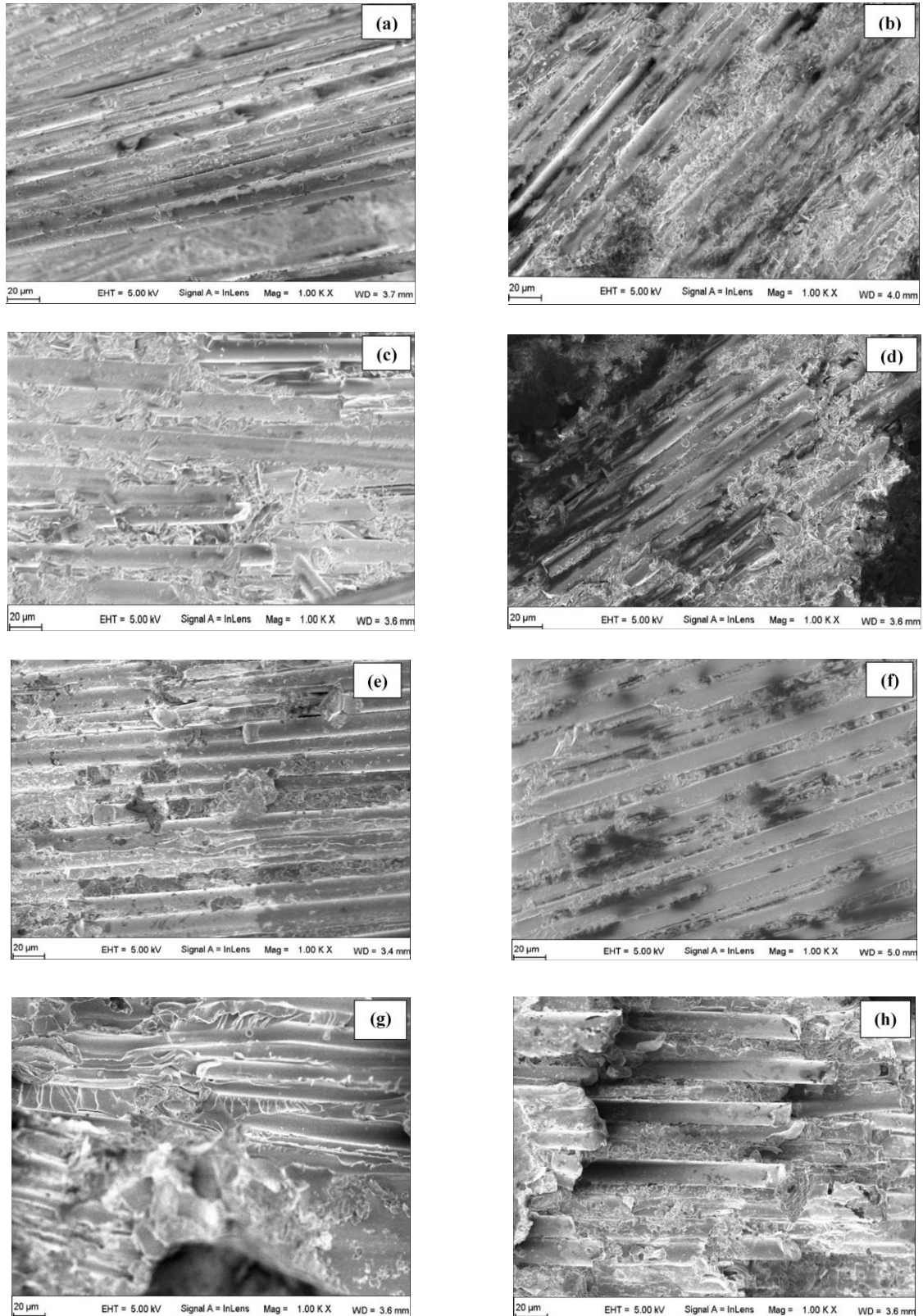
The  $T_g$  of composites was established as per the guidelines of the ASTM E1582-17 procedure. The thermal properties of fabricated samples were measured using the DSC model Q2000 from TA Instruments. The DSC measurements were performed under a nitrogen atmosphere, with the instrument calibrated beforehand using pure indium metal as the reference standard. The DSC runs were carried out within a range of 25-270°C, with a heating rate of 10°C/min. The experimental procedure involved heating a sample powder weighing between 4 to 5 mg, and the absorbed or released heat was determined by comparing corresponding data with that of the reference material.

### 3.2. Thermal conductivity

In the experimentation, an Anter Unitherm TM 2022 TC instrument was used for measuring the TC of the samples, following the guidelines outlined in ASTM E1530-99. The samples employed were circular, measuring approximately 50 mm in diameter and 3 mm in thickness. During the measurements, samples were placed in the TC instrument at 50°C (compressive load: 280 kPa). A period of thermal equilibrium was permitted to be established, and the corresponding TC outcomes were subsequently recorded.

## 4. Results and discussion

This investigation is focused on assessing the impact of nano and micron-fillers on the thermal characteristics of fabricated samples. This assessment is conducted through Field Emission Scanning Electron Microscope (FE-SEM), DSC, TGA, and TC measurements using both theoretical models and experimental methods. The detailed results obtained from these analyses are presented in this section.



**Fig. 3:** FE-SEM images of a) GE b) GEA c) GES d) GESiC e) GEC5 f) GEC10 g) GECM and h) GEG composites

### 4.1. FE-SEM analysis

The FE-SEM analysis was used for understanding the salient features of the morphology of hybrid composites, as the properties of glass fabric reinforced epoxy composites considerably depend on the interaction between micro and nano fillers, ECR glass fabrics and epoxy matrix. An approximation of the distribution of fillers and fabrics in the epoxy matrix was tried by using FE-SEM analysis. The microscopical analysis of the composites reveals that there is a good distribution of the glass fabrics in the base composite (GE), GEA, GES, GESiC, GEC5, GEC10, GECM and GEG as revealed in Figure 3 (a-h).

### 4.2. Differential scanning calorimetry

The distinctions in T<sub>g</sub> of GE and hybrid composites are seen in Figures 4 and 5, respectively. The variations in T<sub>g</sub> of base material and base material with different fillers are predicted in Figure 6.

The T<sub>g</sub> of the epoxy resin was determined to be 137°C, slightly exceeding the manufacturer's datasheet-specified nominal range for T<sub>g</sub>, which typically spans from 120 to 135°C. All composites except for GES, GEA, and GEC10 showed an elevation in the T<sub>g</sub> value. Notably, the T<sub>g</sub> of GES and GEA nanocomposites were within the range of 115-120°C, as documented for analogous resin systems

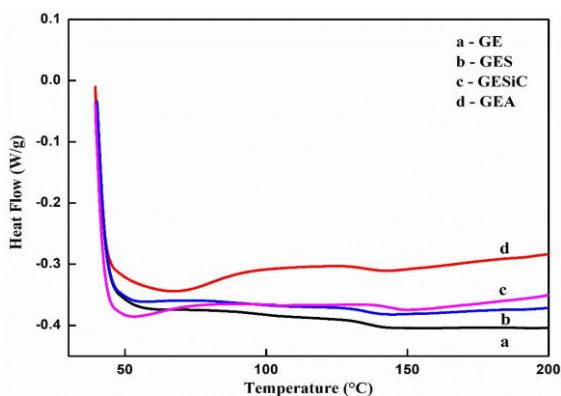


Fig. 4: DSC thermograms of GE, GES, GESiC & GEA

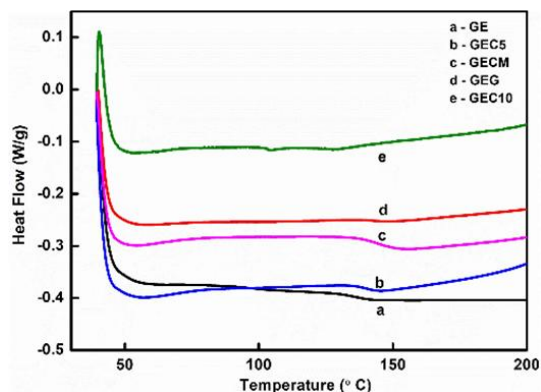


Fig. 5: Heat flow v/s temperature for GE, GEC5, GECM, GEG and GEC10

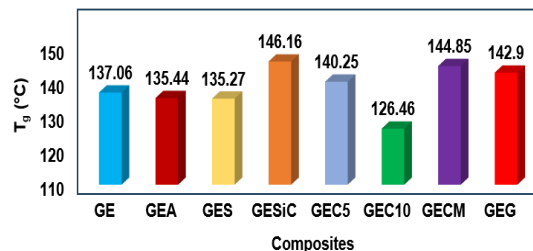


Fig. 6: The T<sub>g</sub> of hybrid composites

incorporating nanofillers<sup>26</sup>). However, the integration of hybrid fillers resulted in an enhancement of the T<sub>g</sub> values for these composites. This suggests that the hybrid filler combination has a notable impact on increasing the T<sub>g</sub> of the composites compared to individual nanofillers.

### 4.3. Thermal conductivity

(i) Theoretical modelling of TC

The following analytical models were utilised for the prediction of TC in the hybrid composites: parallel model, series model, geometric model, and Rayleigh model. Figure 7 presents a contrast between the experimental values and theoretical predictions of TC for the composites based on these models.

The high thermal conductivity of the MoS<sub>2</sub>-containing composite is attributed to the layered structure of MoS<sub>2</sub>, which forms continuous thermally conductive networks within the matrix. Additionally, the high intrinsic thermal conductivity (~85 W/m·K) and good interfacial bonding characteristics of MoS<sub>2</sub> facilitate efficient phonon transport, surpassing other fillers like graphite and SiC in this hybrid configuration<sup>29, 30</sup>.

The parallel model, expressed by equation 1, represents the simplest approach for assessing the TC of polymers. It considers the volume fraction and TC to predict the overall TC of the material<sup>31</sup>):

$$k_{eff} = (k_g * v_g) + (k_m * v_m) + (k_f * v_f) \quad (1)$$

The basic parallel model has been modified by using two constants, 'A' and 'B' and the modified equation is as follows:

$$k_{eff} = A (k_g * v_g) + (k_m * v_m) + B (k_f * v_f) \quad (2)$$

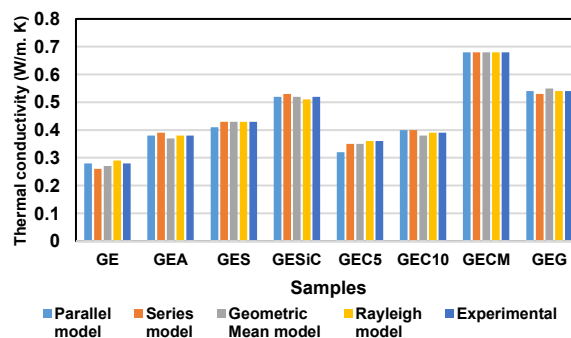


Fig. 7: Thermal conductivity of the hybrid composites

**Table 3:** Constant values in the model

Parameter	GE	GEA	GES	GESiC
A	0.25	0.4	0.33	0.52
B	1	0.025	1	0.025
	GEC5	GEC10	GECM	GEG
A	0.33	0.5	0.78	0.2
B	1	1	0.02	0.02

**Table 4:** Constant values in the model

Parameter	GE	GEA	GES	GESiC
A	1.5	1.0	0.9	0.7
	GEC5	GEC10	GECM	GEG
A	1.0	0.7	1.6	1.4

The modified parallel model used for determining the TC of hybrid composites involves parameters 'A' and 'B', with 'A' ranging from 0.2 to 0.78 and 'B' ranging from 0.02 to 1. The specific values of 'A' and 'B' utilised in this model are provided in Table 3 for different hybrid composites.

The variation in A and B values reflects the differences in interfacial thermal resistance and the formation of the filler network within the epoxy matrix. The composites with high A values (GECM) suggest the presence of more interfacial resistance or filler agglomeration, while lower values (GEG) indicate better dispersion and thermal pathways. The B values closer to unity typically represent the intrinsic thermal behaviour of well-dispersed fillers.

The series model, as described by equation 3, is another basic theoretical model used to estimate the effective TC of composites. It considers the volume fraction and TC of the constituent materials to predict the overall TC of the composite<sup>31)</sup>:

$$k_{eff} = \frac{1}{\left(\frac{v_g}{k_g}\right) + \left(\frac{v_m}{k_m}\right) + \left(\frac{v_f}{k_f}\right)} \quad (3)$$

The basic series model in (3) is also revised for hybrid fillers with a constant 'A' as supported by (4):

$$k_{eff} = \frac{1}{\left(\frac{v_g}{k_g}\right) + A\left(\frac{v_m}{k_m}\right) + \left(\frac{v_f}{k_f}\right)} \quad (4)$$

From Table 4, it is found that the value of 'A' for the hybrid composites ranges from 0.7 to 1.6.

Another model employed to predict the effective TC of hybrid composites is the Geometric Mean (GM) model<sup>32)</sup>, as outlined in equation 5.

$$k_{eff} = (k_g)^{v_g} * (k_m)^{v_m} * (k_f)^{v_f} \quad (5)$$

The GM model, represented by equation 5, is further refined for hybrid composites with the inclusion of two constants, denoted as A and B, as demonstrated in the equation.

$$k_{eff} = A (k_g)^{v_g} * (k_m)^{v_m} * B (k_f)^{v_f} \quad (6)$$

The modified GM model used for determining the effective TC of composites involves constants 'A' and 'B',

**Table 5:** Constant values in the model.

Constant	GE	GEA	GES	GESiC
A	0.52	0.65	0.78	0.85
B	1.0	1.0	1.0	1.0
	GEC5	GEC10	GECM	GEG
A	0.5	0.85	0.7	1.0
B	1.5	1.0	1.0	0.9

**Table 6:** Constant values in the model.

Parameter	GE	GEA	GES	GESiC
A	3.33	1.66	1.25	0.90
	GEC5	GEC10	GECM	GEG
A	1.66	1.42	0.76	0.86

where 'A' ranges from 0.5 to 0.85 and 'B' ranges from 0.9 to 1.5. Table 5 provides the specific values of 'A' and 'B' utilised in this modified GM model for different composites to predict their effective TC. The Rayleigh model<sup>33)</sup> was employed to predict the effective TC of hybrid composites. It is represented by equations 7 to 9.

$$E = k_{eff} = k_m \left[ 1 + \frac{3 * v_f}{\left(\frac{k_f - 2k_m}{k_f - k_m}\right) - v_f + 1.569 \left(\frac{k_f - k_m}{3k_f - 4k_m}\right) * v_f^{\frac{10}{3}}} \right] \quad (7)$$

$$k_{eff} = k_m \left[ 1 + \frac{2 * v_g}{C_1 - v_g + C_2 (0.30584 * v_g^4 + 0.013363 * v_g^8)} \right] \quad (8)$$

where,

$$C_1 = \frac{k_g + E}{k_g - E} \quad C_2 = \frac{k_g - E}{k_g + E}$$

The Rayleigh model expressed in equation 8 is revised for hybrid composites with constant 'A', and the modified equation is shown below:

$$k_{eff} = k_m \left[ 1 + \frac{2 * v_g}{(A * C_1) - v_g + C_2 (0.30584 * v_g^4 + 0.013363 * v_g^8)} \right] \quad (9)$$

From Table 6, it is found that for the hybrid composites, the value of 'A' ranges from 0.76 to 3.33.

The hybrid composites exhibit significantly higher TC compared to the base composite. Among them, the composite with MoS<sub>2</sub> filler demonstrates the highest TC, followed by graphite (GEG) and GESiC. Hybrid fillers, including alumina and silica, also contribute significantly to enhancing TC. The TC values achieved in this study exhibit approximately a 10 to 15% increase compared to those documented in<sup>28)</sup>. The TC of epoxy reinforced with unidirectional glass fibres is reported as 0.2 W/m·K<sup>34)</sup>, but reinforced with woven glass fabric is 0.28 W/m·K.

Constants A and B are empirically derived fitting parameters obtained through regression analysis to match theoretical predictions with experimental results. These parameters effectively account for microstructural effects such as filler–matrix interfacial thermal resistance, heterogeneity in filler dispersion, and void content. Higher A values, for example, suggest increased filler–matrix

interfacial resistance or clustering, while lower values indicate better thermal continuity in the composite structure.

#### 4.4. Thermogravimetric analysis

Figure 8 (a) & (b) depict the thermograms of the samples GE, GES, GEA, and GESiC, while Figure 9 (a) & (b) depict the thermograms of the samples GEC5, C10, GECM, and GEG. The weight loss at diverse temperatures is shown separately for clarity, since overlapping of the thermograms was observed. The temperatures at different derivatives of weight and weight loss are also shown to highlight the differences observed in the composites.

Figure 8 (a) and 9 (a) shows weight loss at diverse phases of the temperature change, namely T<sub>0</sub> (onset of decomposition), T<sub>70</sub> (at 70 % of weight loss), T<sub>80</sub> (at 80 %

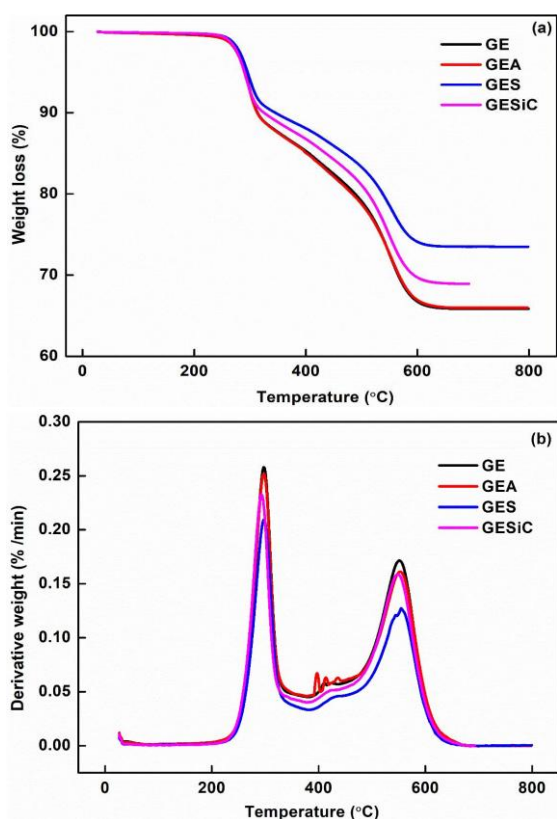


Fig. 8: TGA thermograms: (a) weight loss and (b) derivative weight of the composites

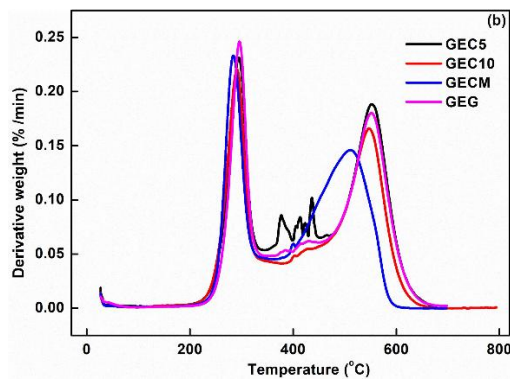
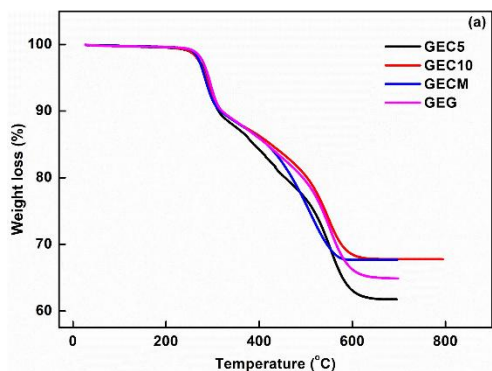


Fig. 9: TGA thermograms: (a) weight loss and (b) derivative weight of the composites.

Table 7: Weight loss at various temperatures as derived from TGA.

Samples	The temperature corresponding to different levels of weight loss ±2 %				
	T <sub>0</sub>	T <sub>70</sub>	T <sub>80</sub>	T <sub>90</sub>	T <sub>max</sub>
GE	225	566	487	305	799
GEA	216	566	480	305	799
GES	220	-	537	340	798
GESiC	237	590	510	325	698
GEC5	220	549	455	313	699
GEC10	213	576	503	317	799
GECM	227	545	470	317	698
GEG	230	565	493	321	680

of weight loss), T<sub>90</sub> (at 90 % of weight loss), and T<sub>max</sub> (maximum temperature). These parameters are employed to assess the thermal stability of the hybrid composites. Table 7 presents the captured weight loss data of the composites at different temperatures.

In TGA, the incorporation of conductive fillers within epoxy composites enhances thermal conductivity but compromises thermal stability, leading to greater mass loss at comparatively lower temperatures. Conversely, the addition of non-conductive fillers tends to improve thermal stability, thereby reducing mass loss at elevated temperatures. These contrasting behaviours are primarily attributed to differences in interfacial bonding strength, phonon scattering at filler–matrix interfaces, and the continuity of thermally conductive pathways formed by the fillers, which impact the composite’s heat transfer characteristics and degradation pathways<sup>35</sup>.

The decomposition temperatures corresponding to various percentages of weight loss are compared to assess the relative thermal stability of the composites. Based on the data in Table 7, it is noted that there is a relative improvement in thermal stability. This observation suggests that incorporating SiC and SiO<sub>2</sub> into the epoxy improves the composites' resistance to thermal oxidation. The hybrid composites exhibit improved thermal stability, initially up to 300°C, characterised by minimal weight loss. However, there is a reduction in the peak of derivative weight loss found around 325°C, compared to the typically

reported range of 350-400°C for nanocomposites. Furthermore, the second peak consistently appears within a range of 580-600°C, irrespective of the filler type employed. Considering the temperature class of the material is crucial for assessing the composite's thermal stability. The observation indicates that the composites exhibit stability within the temperature range of 125 to 135°C, rendering them suitable for applications requiring continuous operating temperatures around 100°C and withstanding occasional spikes in temperature. This attribute improves the transient thermal performance of the composite, a critical factor for diverse industrial applications.

The observed shift in derivative weight loss peak from 350-400°C to 325°C is attributed to the incorporation of conductive fillers such as MoS<sub>2</sub> and graphite, which facilitate localised heat transfer and promote early degradation of the polymer matrix. While this leads to an earlier onset of thermal decomposition, it does not compromise the operational performance in the target application range of 100-200°C. For applications requiring prolonged exposure to temperatures beyond 300°C, further optimisation or alternative filler systems would be necessary.

It is significant to consider the anamorphic of the micron and nano fillers, in addition to the differences in their geometry. Thus, the interfacial area would increase because of the use of the nano filler. However, it would also contribute towards the mismatch of the interfacial area due to the distribution of the two fillers. However, no serious deterioration in the thermal performance of the composites was found. Conversely, an improvement in T<sub>g</sub> is evident in all the hybrid composites.

In polymer composites, fillers such as SiC, MoS<sub>2</sub>, and graphite tend to establish thermally conductive pathways, facilitating phonon transfer b/w the fillers and the polymer<sup>29</sup>). The molecular chains of the epoxy matrix intertwine with the functional groups on the surface of the fillers, forming an interfacial interlayer<sup>30</sup>).

The incorporation of conductive fillers into the polymer matrix markedly enhances the thermal conductivity of epoxy composites<sup>36</sup>). However, these fillers adversely affect the material's thermal stability, promoting an earlier onset of thermal degradation and increased weight loss rates at lower temperatures relative to neat epoxy or composites containing non-conductive fillers<sup>37</sup>). Non-conductive fillers, such as silica or alumina, typically enhance the thermal stability of epoxy composites<sup>38</sup>). Their incorporation results in reduced weight loss rates at elevated temperatures when compared to composites containing conductive fillers or neat epoxy resin<sup>39</sup>).

## 5. Conclusions

In this research work, the impact of combining micron &

nano particles on the thermal characteristics of hybrid composites has been explored through DSC, TGA, and mathematical models for thermal conductivity. The theoretical models used for predicting TC correlated well with experimental data, validating the usefulness of these models in estimating the thermal properties of hybrid composites. The composites containing hybrid fillers exhibit significant improvement in T<sub>g</sub>, and it has been demonstrated that the combination of fillers contributes to improved thermal stability. Hybrid composites exhibit exceptional thermal stability, featuring a blend of micro & nano particles at 5 wt. % of silica and silicon carbide are much more thermally stable than the other composites. The performance of fabricated composites is relatively better concerning thermal performance in contrast to the individual nano and micron filler-based composites, particularly in the 100 to 200°C temperature range, which is critical for industrial applications of composites. The improved thermal stability and conductivity render these hybrid composites suitable for industrial applications such as high-temperature electrical insulators, thermally managed enclosures, and structural applications in automotive and aerospace sectors. The present study is limited to low filler loadings and static thermal property measurements under controlled laboratory conditions. The impact of environmental factors such as humidity, cyclic thermal loading, and long-term ageing was not evaluated. Future investigations will focus on exploring higher filler concentrations, hybrid filler dispersion optimisation and evaluating dielectric and mechanical properties alongside thermal performance for broader multifunctional application readiness.

## Author's statements

### Contribution:

Bommegowda K B and Roopa B Hegde conducted the experiments, performed data analysis, and contributed to manuscript preparation. Roopa B Hegde additionally reviewed and revised the manuscript.

### Conflicts of interest:

The authors declare no conflicts of interest.

### Data and code availability:

The data supporting the findings of this study are available from the authors based on request.

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## Nomenclature

### Symbols and Units

keff	Effective thermal conductivity of the composite (W/mK)
kg	Thermal conductivity of glass fiber (W/mK)
km	Thermal conductivity of the matrix (W/mK)

kf	Thermal conductivity of the fillers (W/mK)
vg	Volume fraction of glass fiber
vm	Volume fraction of matrix
vf	Volume fraction of filler
Tg	Glass transition temperature (°C)

#### Abbreviations

DSC	Differential Scanning Calorimetry
GM	Geometric Mean
TC	Thermal Conductivity
TGA	Thermogravimetric Analysis

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