Thermal analysis of Kevlar/basalt reinforced hybrid polymer composite

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Abstract

Use of lightweight composite materials in automobile applications such as doors, bonnets, and bumpers and also the utilization of composite materials in building insulations require superior mechanical and thermal properties. This study attempts to determine the thermal conductivity, linear thermal expansion coefficient, heat deflection temperature and thermo-gravimetric analysis of hybrid composite containing reinforcement fibers stacked in seven different combinations in an epoxy matrix as per ASTM standards. Each composite contained two different fibre materials, i.e., Kevlar and basalt. The study revealed that the stacked layers of basalt fibers had more influence on the thermal properties. It was observed that the hybrid composite made of least quantity layers of Kevlar and most of basalt exhibited the maximum thermal conductance of 0.219 W mK⁻¹, while with vice versa laminate developed 0.191 W mK⁻¹ which was least thermal conductance. The composition prepared by made Kevlar as core layer and basalt as its outer layers exhibited coefficient of linear thermal expansion above 11.5 × 10⁻⁶/°C. Maximum decomposition weight loss of 76.92% occurred in the composition prepared by keeping basalt as core and Kevlar as outer layer. The differential thermal graph showed that the said hybrid composite exhibited the peak decomposition rate of 1 wt. %/°C. The thermal properties of the laminate prepared by keeping two layers of Kevlar sandwiched between the basalt were excellent when compared to other six hybrid composites investigated in this study.

1. Introduction

Atleast two or more materials having distinctively different properties combined together to form a Composite which was superior in performance (Abdel-Magid et al 2005, Herrera-Franco and Valadez-González 2005, Dhakal et al 2007, Rao et al 2010, Prasad and Rao 2011). They have gained wide spread use around the globe for their customizable properties (Vinod et al 2021a, 2021b). Some of the applications that employs composite materials include automobile bonnets, bumpers, and dashboards, partition walls in buildings and locomotives, as well as marine materials (Langdon 2007, Carrillo and Cantwell 2009, Adema et al 2015, Okereke 2016, Mania and York 2017). Composite materials having two or more reinforcement materials as their composition are classified as hybrid composite materials. These materials are in high demand for applications extending from scientific equipment, industrial products and domestic uses (Calabrese et al 2020). They are used to make the composites determine the properties exhibited by them. One of the preferred materials to make composites is Kevlar. The benefits exhibited such as superior tensile strength, lightweight, excellent impact strength, and thermal stability by Kevlar have been mentioned in many research articles (Sorokin and Kurakin 1984, Pohl and Pfalz 2010, Madhavi and Rao 2017). Basalt is yet another material that has been widely chosen as a reinforcement for composites due to its availability and easy processing ability (Maurya et al 2015, Iskender 2016, Rajesh et al 2018). The two materials have been used as hybrid reinforcement to enhance its mechanical and metallurgical characteristics (Fernando 2009, Singh and Samanta 2015, John 2017, Bandaru et al 2018). Fragassa et al (2018) produced a hybrid flax and basalt reinforced vinyl ester composite. Their study showed the possibility of synergistic behavior between the two reinforcement fibers. As the result, the hybrid composite exhibited...
superior tensile strength, reduced stiffness, and brittleness. Bandaru et al (2017a, 2017b) attempted to make the composites in 2D plain woven and also 3D angle interlock arrangement for ballistic applications.

Most studies have been carried out to find its characteristics under static conditions. There has been little focus on analyzing the thermal behavior of hybrid composites (Liu et al 2014, Chen et al 2017, Dong et al 2017, Guillou et al 2018, Bachtiar et al 2019, Javanbakht et al 2019, Ramesh and Anand 2019, Mohanavel et al 2021). Bachtiar et al (2019) used flax fiber-based polymer composite to study fire resistance. They dispersed ammonium polyphosphate and aluminum hydroxide in varying weight concentrations (10 to 40%). Thermogravimetric analysis revealed that the composites attained self-extinguished behavior when the concentration of ammonium polyphosphate was between 20% and 30%. Bard et al (2019) inferred the influence of volume concentration of carbon fibers over the thermal conductance of epoxy matrix composite. They measured the thermal conductance along with the linear and lateral directions of the fibers. They found an exponential increase in thermal conductance along the lateral direction of the carbon fibers (Vinod et al 2021a, 2021b).

Thermal conductance of composite material containing hemp as the reinforcement and polymer matrix was studied by Behzad and Sain (2007) and Sayyidmousavi et al (2019). They compared the thermal conductance of the composite material measured experimentally. They observed good correlations among the theoretical models with experimental work. Hartlieb et al (2016) assessed the thermo physical characteristics of composites containing granite, sandstone, and basalt as the reinforcement material. They observed that phase transition occurred between 25 and 1000 °C, which influenced its texture and stability (Yashas Gowda et al 2021).

Studies reveal that the properties exhibited by the composite materials depend on the factors like materials chosen as its composition and stacking sequence (Alamri and Low 2012, Zeng et al 2016, Zhang et al 2016, Bandaru et al 2016, 2017a, 2017b, Hu et al 2017, Chegdani and Mansori 2018, Bachtiar et al 2019, Calabrese et al 2020). Proper selection of components for the composite material can facilitate effective thermal conductance (Islam and Pramila 1999). The influence of fibre orientation in the composite materials, the thickness of the produced composite, and interfacial characteristics impact the thermal conductance (Sweeting and Liu 2004). Increasing reinforcement volume concentration can increase the thermal properties of the composite. This can exceptionally increase its thermal conductance, provided that the reinforcement materials are evenly dispersed in the composite (Javanbakht et al 2019). The orientation of fibers shows an imperative role in the characteristics exhibited by the composite. The thermal conductance of composite was having unidirectionally laid Manila hemp as reinforcement and epoxy resin/poly-lactic acid as the matrix was found to reduce by 33.33%. However, its weight fraction increased by the range of 40 to 69% (Osugi et al 2009). Upto 8% reduction in the thermal conductance was noted when glass fiber (15.7 vol. %) was used as the reinforcement. However, the same quantity of banana fibers, reduced the thermal conductance by 12% (Sahu 2014). Glass, Carbon, and Kevlar reinforcement materials can influence the loss of weight during Thermal Gravimetric Analysis (TGA). It can also change the thermal degradation temperature of the composite materials (Ravichandran 2016). Factors such as fiber diameter, aspect ratio, defects in the produced composites can also influence the thermal properties exhibited by the composite (Vilchevskaya and Sevostianov 2016).

An attempt is made through this study to determine the thermal conductance, coefficient of thermal expansion, heat deflection and TGA of seven different hybrid Kevlar and basalt reinforced epoxy composite.

### 2. Experimental work

#### 2.1. Selection of materials and stacking sequence

The reinforcement used for the present study is based on 300 GSM of Kevlar and basalt fibers. The matrix element for producing the composite was made using a 10:1 ratio of LY556 (resin) and hardener HY951 (hardener). The hybrid composite was prepared using the hand layup technique (Ramesh et al 2013a, 2013b, Saba et al 2015, Ravichandran 2016, Jabbar et al 2017, Rajeev Kumar 2017, Harikrishna et al 2018). Table 1 shows the general properties of the reinforcement fibers used for this study.

| Properties          | Kevlar | Basalt | Units      |
|---------------------|--------|--------|------------|
| Density             | 1.44   | 2.65   | g cm⁻³     |
| Tensile strength    | 3.6    | 4.8    | GPa        |
| Modulus of elasticity | 62    | 110    | GPa        |
| Elongation percentage | 2.8  | 3.1    | %          |
| Poisson’s ratio     | 0.44   | 0.2    |            |
| Thermal conductivity| 0.04   | 1.62   | W mK⁻¹     |

Table 1. Properties of Kevlar and Basalt fibers.
The reinforcement fibers were placed over a waxed sheet in a steel frame (300x300x3mm³). The matrix element was laid in between the reinforcement to serve as the binding element. It was evenly dispersed over the reinforcement fibers by using a mechanically operated roller, gently rolled at 45° to the fiber orientation. Each layer of the reinforcement fibers was placed such that the fibers lay orientated with each other. Another layer of the waxed sheet was placed over the top layers of the stacked composite. A load of 15 kg was placed over the hybrid composites for 24 h during the production process to allow the composition to cure and set. A total of six different stacking sequences were used in this study as shown in figure 1. Each of the composites had seven layers in which the reinforcement materials were stacked in different combinations as shown in figure 2. Each stacking sequence was coded as U, V, W, X, Y, and Z - composites for identification. The volume fraction of the hybrid composites used for this study is shown in table 2. The formula used for calculating the fiber volume fraction is given in the below equation (1) and it is as per the reference by Yashas Gowda et al. 2021.

\[
V_f = \left( \frac{W_b}{\rho_b} + \left( \frac{W_k}{\rho_k} \right) \right) / \left( \frac{W_b}{\rho_b} + \frac{W_k}{\rho_k} + \frac{W_m}{\rho_m} \right) \tag{1}
\]

Where,
- \(W_b\) - weight of the basalt fiber,
- \(\rho_b\) - density of the basalt fiber,
- \(W_m\) - weight of the matrix,
ρm - density of the matrix,
Wk - weight of the Kevlar fiber,
ρk - density of the Kevlar fiber.

The void fraction of the hybrid composites was determined by the equation (2) and it is as per the reference by Jawaid et al 2011, Vinod et al 2021a, 2021b.

\[ \nu_f = \frac{\rho_t - \rho_a}{\rho_t} \]  

Where

\( \nu_f \) is the void fraction of the hybrid composites (%),
\( \rho_t \) is the theoretical density of the hybrid composite (g cc\(^{-1}\)),
\( \rho_a \) is the actual density of the hybrid composite (g cc\(^{-1}\)).

The theoretical density of the hybrid composites is measured as the sum of the densities of the individual composition. The actual density is measured for the six different hybrid composites. The density exhibited by the respective reinforcement fibers was determined respective to their volume fraction. Similarly, the actual density of the epoxy resin was also calculated. The resulting values were added to find the actual density. The values of void volume fraction are given in table 3. Since the value of the volume fraction of void is less than 1% for all the laminate configurations, its presence may be omitted as per the literature.

2.2. Material characterization

The thermal conductivity, heat deflection temperature (HDT) and coefficient of linear thermal expansion (CLTE) evaluated on the six fabricated hybrid composite under ASTM Standards. Equation (3) shows the formula to determine the thermal conductance of the hybrid composites produced for this study.

\[ k = \frac{ql}{\Delta T} \]  

where \( k \) was the thermal conductance (W mK\(^{-1}\)), \( q \) denotes the heat flux found using the equation shown in (4), \( l \) was thickness, and \( \Delta T \) was difference in surface temperatures.

\[ q = \frac{Q}{A} \]  

where \( Q \) was the heat transfer rate and \( A \) was area of cross-section of the hybrid composite.

Specimen of size 2 cm \( \times \) 2 cm were cut from each composite to carryout Thermo-Gravimetric Analysis (TGA). Each specimen was subjected to TGA using TA Instruments make (Model: V45). Simultaneously, the Differential Thermal Graph (DTG) was obtained for each specimen. The specimen was first heated in an inert atmosphere with nitrogen gas till 600 °C to find its decomposition characteristics (Akay et al 1997, Mir et al 2010, Pang et al 2015, Szolnoki et al 2015, Ramesh 2016, Ramesh and Anand 2019). Then the atmosphere was switched to standard air to determine its oxidation behavior (Raja and Anand 2019). The heating rate was maintained at 10 °C min\(^{-1}\) throughout the TGA (Mohanavel et al 2021).

3. Results and discussions

3.1. Thermal conductance

The thermal conductance of the hybrid composite was illustrated in figure 3. It was observed that the specimen ‘W’ had the maximum thermal conductance of 0.219 W mK\(^{-1}\) among the hybrid composites made for this study. The said hybrid composite had basalt fibre that was sandwiched by the Kevlar fibers. This was inturn sandwiched by the outer layers of basalt fibers. The hybrid composite ‘Z’ had 3.7% lower thermal conductance than ‘W’. This had two successive layers of the Kevlar fibers sandwiching the middle three layers containing
basalt fibers. The hybrid composite ‘X’ developed 7.8% lower thermal conductance than ‘W’. Among the six hybrid composites, ‘Y’ exhibited the lowest thermal conductance of 0.191 W mK$^{-1}$. This is because combining two or more layers of basalt fibers facilitates heat transfer while combining two or more layers of Kevlar fibers reduces the heat transfer capability of the hybrid composites.

For the stacked sequence ‘U’ and ‘V’, the thermal conductance was 0.199 and 0.197 W mK$^{-1}$ respectively. The hybrid composite ‘V’ had four layers of Kevlar fibers. Interestingly, the hybrid composite that had outer two layers of basalt developed 7.67% more thermal conductance when equated to its equivalent ‘U’. The hybrid composites ‘Y’ and ‘Z’ had three consecutive layers crammed by the other material. This combination increased the thermal conductance by 9.5%. In another work, the developed composite of neem and banyan fibers was revealed the thermal conductivity of 0.168 W mK$^{-1}$, therefore, compared to this results 0.8% higher thermal conductivity was identified when utilized the combination of Kevlar and basalt fiber composite (Raja and Anand 2019).

### 3.2. Coefficient of linear thermal expansion

Coefficient of linear thermal expansion of the hybrid composites depicted in figure 4. It was witnessed that composite containing Kevlar as the outer layers (V, X, and Z) exhibited 8.24, 9.26, and 8.93 × 10$^{-6}$/°C. The heat transfer occurred isotropically because of the cross-ply weaving of the reinforcements (Mittal et al 2018). The epoxy resin which acted as the matrix material contributed to heat transfer. This allowed an increase in
CLTE. It was observed that basalt had a good binding property with the epoxy resin that allowed the increase in heat transfer. The matrix element dispersed properly within the layers of the basalt fibers, allowing the CLTE to increase in, ‘U’, ‘W’ and ‘Y’ respectively. Figure 3 shows that the CLTE of the hybrid composites with Kevlar as the out layers reduced by 20%~29.6%.

3.3. Heat deflection temperature
The HDT obtained for six diverse stacked sequences were given in figure 5. The short term heat resistance can be identified by using this heat deflection test, (Karthik Babu et al 2020). It was noted that the HDT of each hybrid composite varied concerning the stacking sequence. The highest heat deflection temperature of 103.4 °C kg⁻¹ was exhibited by the hybrid composite coded as ‘U’. This composite had alternating layers of basalt and Kevlar 29 reinforcement fibers. Each of these reinforcement fibre layers was properly separated by the matrix material.

The alternating layers of the reinforcement fibers benefited by acting as insulating layers. Because of this, the matrix material was able to sustain higher temperatures compared to all other stacking sequences used in the
research. Since the hybrid composite ‘U’ was capable of sustaining higher temperatures, it can act as a suitable candidate for applications demanding insulation.

3.4. Thermo–gravimetric analysis
The TGA curves and DTG for the six composite materials were shown in figures 6–11. All the specimens revealed TGA with three steps depicting the decomposition of volatile materials, followed by pyrolysis and composition.
Decomposition and pyrolysis occurred in the inert atmosphere, whereas the combustion took place in standard air, (Ghasemi et al 2018, Guillou et al 2018). However, the extent of decomposition and combustion were different for every composite in the study. The influence of the stacking sequence was noted with the weight loss percentages in the composites. The DTG curves revealed that exothermic reactions took place during the decomposition, pyrolysis, and combustion process.

The weight loss exhibited by the composites and the peak values of heat of reaction is given in table 4. It was noted from the table that weight loss due to decomposition is over 55% irrespective of the stacking sequence.
Much of the decomposition had occurred because of the presence of monomers in the matrix element. This was justified by observing the heat of the reaction curve which revealed that the majority of the exothermic heat has been liberated during decomposition.

The influence of the stacking sequence can be observed from the weight loss during combustion. In the case of composite U and V, the reinforcements Kevlar and basalt were stacked alternatively. Their weight loss was closer to each other. However, stacking twin layers of the same materials as the outer layers brought wide variation in the weight loss percentage. However, the quality of combustion was relatively good in the case of composite X. This was justified by observing the weight loss of the residue.

It was noted that combining two layers of Kevlar improves the TGA property of Kevlar-basalt hybrid composite. However, the use of a tri-layer of Kevlar improvises the TGA property to a greater extent. In the case of composite Y having three subsequent layers of Kevlar sandwiched between bilayers of basalt fibers, the weight loss during combustion reached the peak value of 14.74%. The DTA peak for the same composite was comparatively higher at 0.66 wt. %/°C.

4. Conclusion

- The influence of stacking sequence on the thermal properties of composites was analysed. The thermal conductance of the hybrid composite was enhanced by polymer matrix.
• The matrix element had an affinity with the basalt which resulted in enhanced thermal conductance of the hybrid composite coded as ‘W’ by 8.41% compared to its counterpart coded as ‘X’. Due to the presence of five layers of basalt fibers in the hybrid composite ‘W’ resulted in enhancing the thermal conductivity of the hybrid composites.

• The coefficient of linear thermal expansion of the hybrid composite having basalt fibre as its outer layers exhibited a prominent value of $11.6 \times 10^{-6}/^\circ C$. However, the heat deflection and Kevlar as its outer layer increased by as much as 103.6 °C kg$^{-1}$. This shows that the Kevlar fibers in the hybrid composites increased the insulating property.

• Thermo-Gravimetric Analysis was carried out on six hybrid composite materials made of Kevlar and basalt fibre reinforcement. The analysis revealed that the hybrid composite coded as ‘X composites’ had the peak values in the form of weight loss percentage. However, in all the samples was given the thermal stability upto 300 °C of hybrid composite, it can be used to superior temperature applications.

• The observations showed a raise in the decomposition weight loss by as much as 13.36% and combustion weight loss by 58.45% compared to its counterpart designated as ‘W - composites’. However, its residue increased by 1.61 times compared to ‘X - composites’. Likewise, the hybrid composite ‘W - composites’ exhibited a lower DTA peak at 0.93, 0.1, and 0.25wt.%/°C, compared to its counterpart ‘X - composites’.

• Among the six hybrid composites studied in these investigations, the one designated as ‘W - composites’ developed enhanced thermal conductivity, CLTE, TGA, and DTG plots. Therefore, the basalt fibre loading was given the significant thermal properties compared to Kevlar fibre loading of the hybrid composites.

**Data availability statement**

All data that support the findings of this study are included within the article (and any supplementary files).

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