Peddakondigalla *et al.*
Journal of Engineering and Applied Science (2024) 71:113
https://doi.org/10.1186/s44147-024-00448-0

Journal of Engineering and Applied Science

RESEARCH **Open Access**

Investigation on mechanical and thermal behaviour of graphene bonded carbon/Kevlar hybrid fabric polymer composites

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Abstract

The present research is aimed to understand the influence of graphene-reinforced carbon/Kevlar hybrid fabric epoxy composites. Samples HG0, HG2, HG4, and HG6 are fabricated using four layers of fabric mat and with varying graphene weight percentage as 0, 2, 4, and 6 wt.%, respectively. Mechanical characterizations such as hardness, tensile, and flexural strength were individually assessed. Thermal stability is evaluated through thermos-gravimetric analysis. Composite HG6 with high filler loading showed 71% and 114.4% greater tensile and flexural strength compared to unfilled HG0 specimen. Similarly, HG6 exhibited greater thermal stability. Inclusion of graphene particles in higher concentration improved the interfacial bonding between fibre/matrix/filler system. Fracture surfaces are analysed using scanning electron microscopy to understand the failure mechanisms.

Keywords: Carbon/Kevlar hybrid fabric, Graphene, Mechanical strength, Thermogravimetric analysis, Polymer composites

Introduction

Polymer composites are extensively utilized for structural applications in automotive, chemical, and medical industries owing to their lighter weight components that are combined with superior thermal, mechanical, and chemical properties [1–4]. Polymer matrix particularly epoxy resin is commonly employed as structural adhesive by reinforcing with different types of fibres and fillers. Epoxy-based composites possess high specific strength, fabrication ease, chemical resistant, and less cost. These composites find their applications in aircraft engine blades, pipe lines for petroleum refining, high speed vehicles, and impeller blades [5–7]. Polymer composites strengthened with fibres often referred as fibre-reinforced composites (FRPs) exhibit excellent mechanical strength, but they are weakened owing to brittle nature of matrix material. To overcome such drawback, appropriate micro or nano filler is added to develop fibre/matrix/filler system [8–10].

Kevlar fibres exhibit high strain and neither melt or decompose at higher temperatures (>450 °C). Carbon fibres are popularly used for aerospace applications owing to good specific strength and stiffness [11, 12]. Hybridization of two fibres can enhance compressive strength, impact toughness, weight reduction, and strain capability of composite laminates. Although better properties were reported with hybridization, yet the further improvements are necessary to meet varied design conditions [13, 14]. Thus, filler particles are added to obtain beneficial effects to hybrid fibre composite configurations. In the current industrial scenario, carbon-based particles such as carbon nanotubes, carbon black, graphene, and graphite emerged as novel filler materials. Integration of graphene particles into the epoxy resins showed promising results by enhancing the properties of composite materials [15–17]. Graphene particles comprise two-dimensional carbon atoms in mono layers. Due to this, better dispersibility can be achieved with polymer matrices. Besides, they are able to improve mechanical and thermal properties, damping characteristics and corrosion resistance of composites [18–20].

A study presented by Alexopoulos et al. [21] proved that addition of graphene nano particles increased the tensile and fracture toughness of epoxy composites by 15% and 12%, respectively. Another study by Salom et al. [22] showed the enhanced storage modulus in graphene/epoxy composite materials at optimum filler loading. At higher concentration, the properties tend to decrease. Li et al. [23] stated in his literature review that incorporating graphene layers in polymer matrices improve their mechanical characteristics. Cho et al. [24] added graphene particles to carbon fibre/epoxy composites and observed 16% and 18% increase in compressive and in plane shear strengths respectively. Moreover, graphene also enhanced tensile, flexural, and impact strengths of glass fibre/epoxy composites as reported by Aswathnarayan et al. [25]. The interfacial interaction between graphene and fibres improves the structural stability of epoxy composites. From the literature, it was observed that limited research was reported on graphene-based fibre-reinforced composites. On the other hand, hybridization of fibres was presented by researchers, but the studies pertaining to hybrid fabric was not explored so far. Thus, the novelty of present research lies in utilizing the hybrid fabric mat comprising carbon as warp and Kevlar as weft in epoxy matrix along with graphene particles. Such fibre/matrix/filler composite configuration is experimentally tested to understand the mechanical and thermal characteristics.

Materials and methods

Hybrid mat as shown in Fig. 1 comprises carbon as warp and Kevlar as weft 200 gsm taken as fibre material. Graphene having an average particle size of 15 μm with 99% purity is chosen as filler. Epoxy resin LY-556 is utilized as a polymeric matrix along with a curing agent HY-951. Properties of raw materials used in the fabrication process are given in Table 1.

Fabrication of hybrid composites

Initially, the hybrid fabric mat was cleaned using acetone to remove any dust particles present on it. It was then dried at 60 °C in a vacuum oven for 3 h to remove the moisture completely. Degassing of epoxy resin was done to eliminate the air bubbles. Graphene taken in different weight percentages (0, 2, 4, and 6%) was added to epoxy in individual

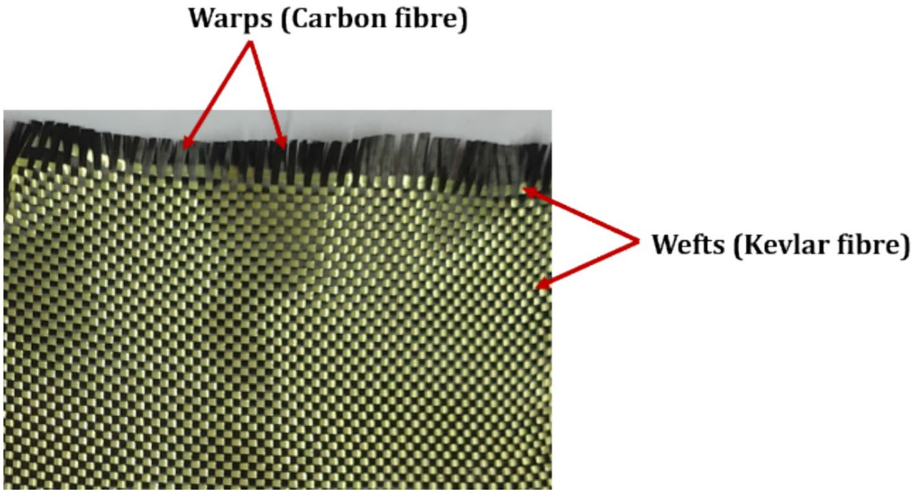


Fig. 1 Carbon/Kevlar hybrid fabric mat

Table 1 Properties of raw materials

Constituents in composite samples	Density (g/cc)
Hybrid mat	1.63
Graphene	0.3
LY-556 epoxy	1.15–1.20
HY-951 curing agent	0.98

containers. To ensure uniform dispersion of graphene in epoxy, the containers were subjected to ultrasonic bath sonicator as supplied by Samarth Electronics by maintaining a temperature of 60 °C for 3-h duration. After sonication, the curing agent was added to the epoxy mixture in 10:1 ratio. The composites were fabricated in a wooden mould of volume $200 \times 200 \times 4$ mm^3 through lay-up lamination process. Four layers of hybrid fabric mat were placed in a wooden mould, and then epoxy mixture was added to it. Samples were left out for curing at room temperature for 72 h. Composite fabrication is represented through Fig. 2. Composites were designated as HG0, HG2, HG4, and HG6 which corresponds to filler weight percentage.

Hardness

Hardness of composite specimens is evaluated on RS Scientific FMV1-MC-AT micro Vicker's hardness testing apparatus present at Vellore Institute of Technology, Andhra Pradesh. Samples were tested following ASTM E384-17 standard by applying a load of 1 kg for a dwell period of 15 s. For each composite, three readings were taken, and their mean value was noted. Hardness number in terms of HV is calculated using the formulae reported in the literature [26].

Thermogravimetric analysis

Thermogravimetric analysis (TGA) is performed on PerkinElmer thermal analyser available at Vellore Institute of Technology, Andhra Pradesh, to understand the thermal stability.

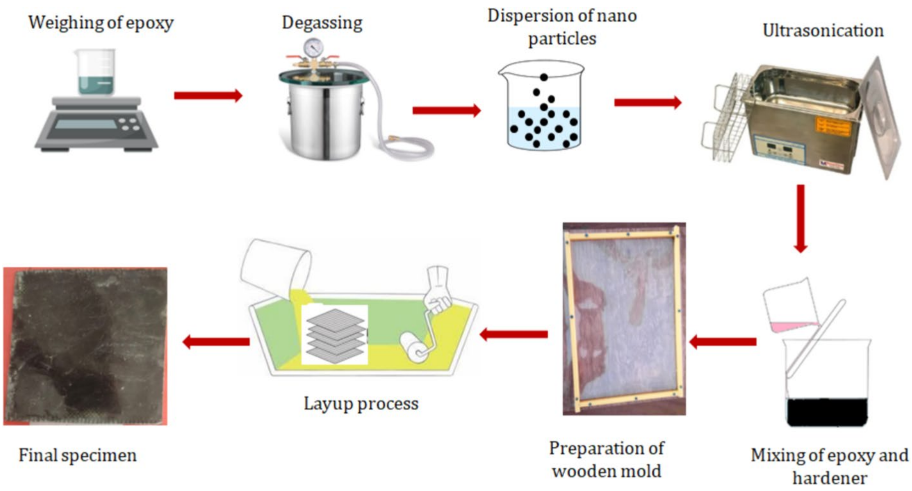


Fig. 2 Schematic diagram for composites fabrication

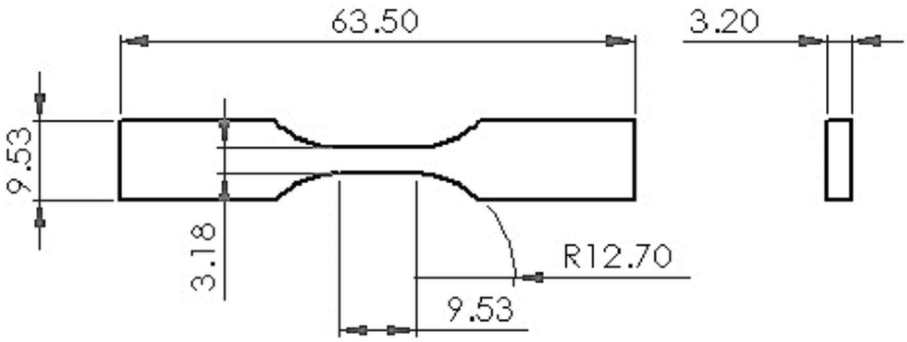


Fig. 3 ASTM D638 standard figure for tensile testing

Specimens were heated in the inert atmosphere from 30 °C to 700 °C maintaining a constant rate of 15 °C min^{-1}, and the corresponding weight loss (in %) was recorded.

Mechanical testing

Mechanical strength in terms of tensile and flexural was evaluated on Tinius Olsen H10KL UTM facility available at Vellore Institute of Technology, Andhra Pradesh, following the ASTM D638 and D790 standards respectively. For tensile testing, ASTM D638 type V sample having overall length of 63.5 mm and a width and gauge length of 9.53 as displayed in Fig. 3 was utilized. Crosshead strain rate of UTM is maintained constant at 1 mm/min^{-1}. Three identical specimens from each composite were tested, and their average value is adopted for result analysis. After testing, the surface of fractured samples was analysed under SEM to understand failure mechanisms.

Results and discussion

Hardness

Vickers hardness (in HV) of all composite samples is shown in Fig. 4. Results depicted that specimen filled by 6% graphene, i.e. HG6, exhibited high hardness number of 92 HV compared to other composites due to better dispersion of filler particles and their bonding with the fibre and matrix. Nearly 27.7% increment in hardness was observed from HG2 to HG6. As the filler loading is increased, the interparticle distance in the matrix decreases which provide resistance to indentation [27]. Thus, the composite specimen HG6 with more filler particles displayed greater hardness. On the other hand, HG0 having 0% graphene exhibited least hardness of 54 HV due to weak bonding between fibre and epoxy. Hardness improved by 33.3%, 57.4%, and 70.3% for HG2, HG4, and HG6, respectively, as compared to HG0.

Thermogravimetric analysis

TGA analysis was performed in the nitrogen atmosphere, and the obtained results are represented in Fig. 5. From the curves, it was evident that early degradation of composites took place around 330–350 °C. During this temperature, the moisture and wax in the samples evaporate and resulted in maximum weight loss [28]. On further increase in temperature, the decomposition of polymer chains was initiated. The presence of graphene significantly affected the thermal stability of hybrid carbon/Kevlar epoxy composite laminates. Sample HG6 exhibited greater stability with 59.6% residue which indicates its more char formation, while HG0 possess least thermal stability and formed 39.1% of solid residue. Likewise, the char formation in the composites HG4 and HG2 was observed as 42.7% and 40.3%, respectively. Increasing sequence of thermal stability of all samples follow the order as HG6 > HG4 > HG2 > HG0. Greater stability of HG6 is mainly due to better thermal response and dispersibility of graphene particles in the

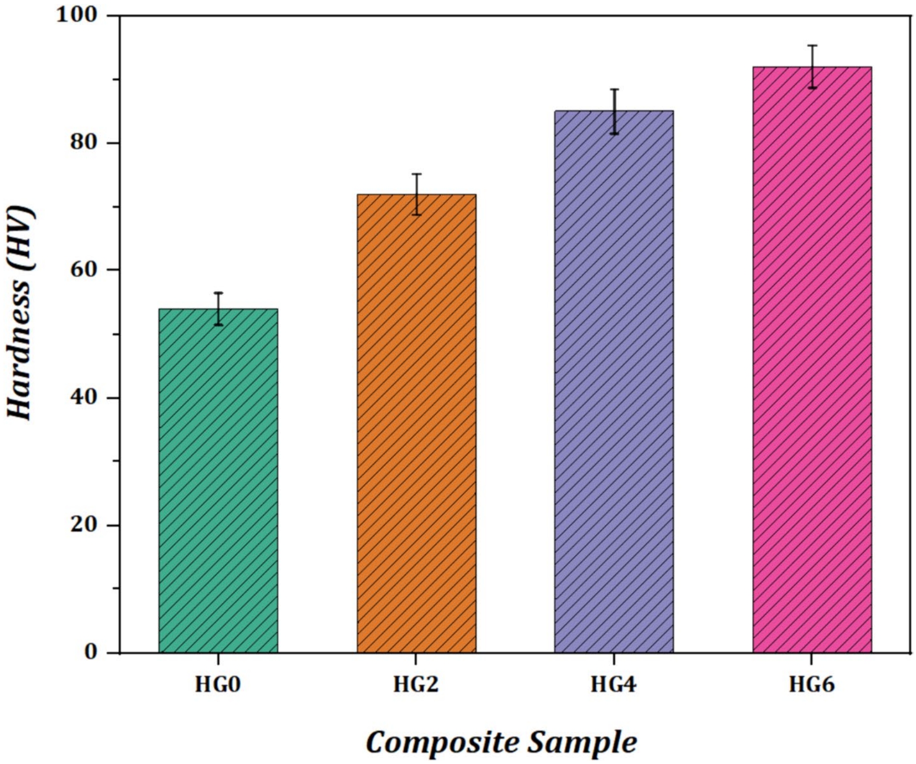


Fig. 4 Vickers hardness of composite laminates

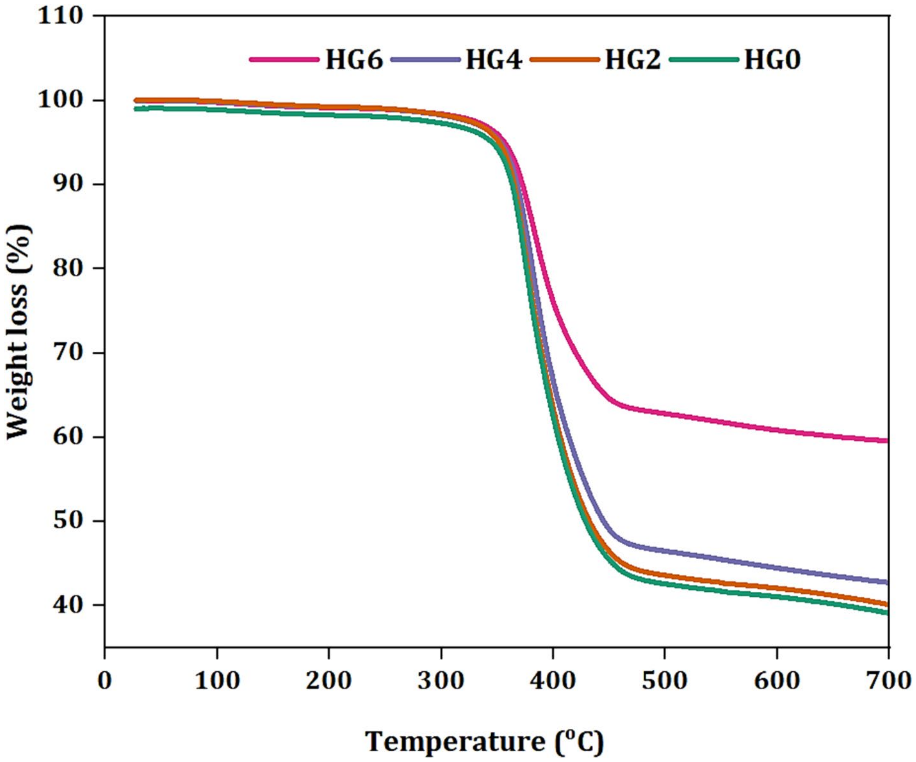


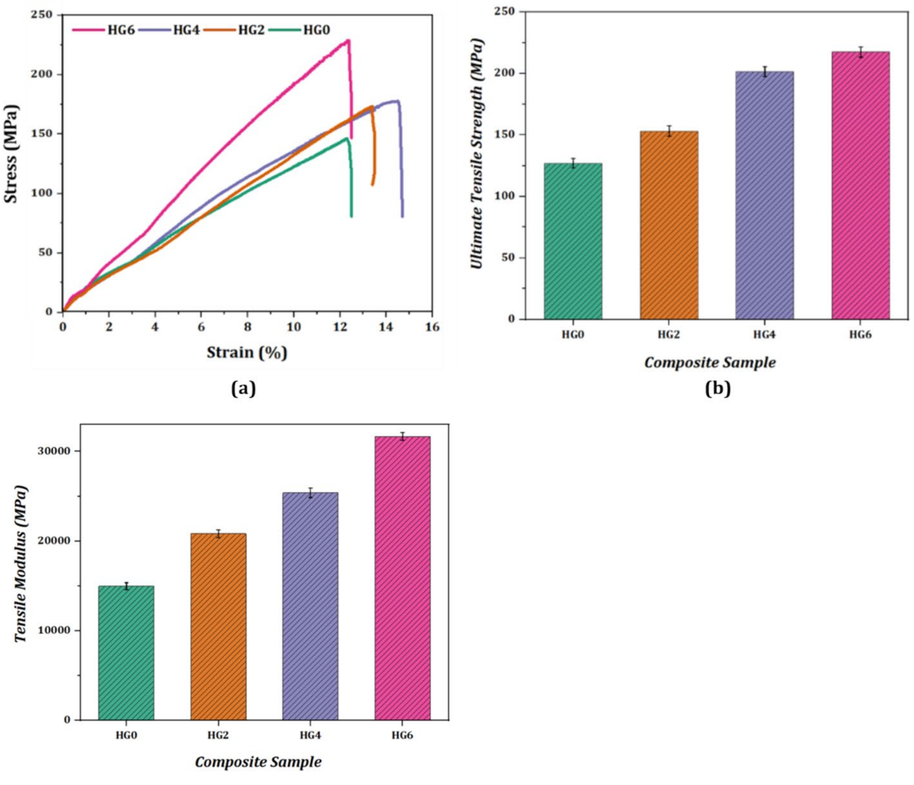
Fig. 5 TGA curves of composite samples

epoxy. Moreover, the aromatic rings present in the Kevlar were highly cross linked with the epoxy which also effects the thermal stability [29].

Mechanical testing

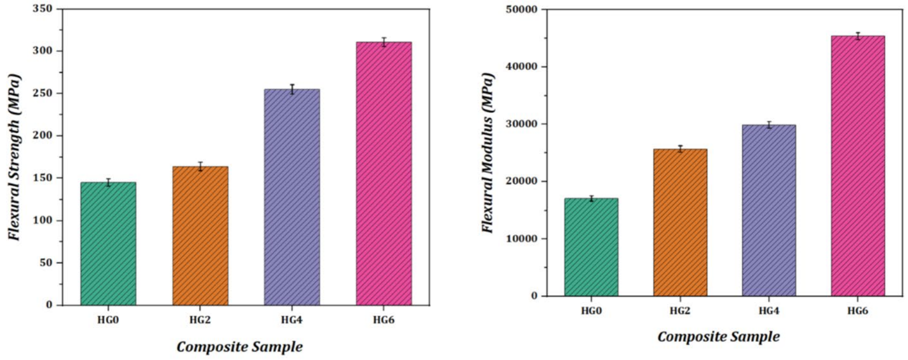
Figure 6a–b represents the tensile stress–strain graph and ultimate tensile strength (in MPa) of composites. The specimens showed a linear variation indicating their nature as brittle. Addition of graphene particles further increased the brittleness and improved the tensile strength of hybrid carbon/Kevlar epoxy composites [30]. Highest strength of 217.2 MPa was shown by HG6, while the least strength of 126.9 MPa exhibited by HG0 among all composite configurations. Composites with graphene particles displayed superior strength due to their dispersibility and better load carrying capability. The tensile strength was improved by 41.8% as graphene content increased from 2 to 6%. Further, the increment of 20.62%, 58.6, and 71% was observed for HG2, HG4, and HG6 compared to HG0 composites. The increasing sequence of tensile strength of all specimens follows the order as HG6 > HG4 > HG2 > HG0. On the other hand, tensile modulus for the sample HG6 was also reported to be higher as evident from Fig. 6c.

Flexural strength (in MPa) corresponding to all the composites is represented in Fig. 7a. Samples showed increased strength with an increase in graphene particles. Flexural strength improved by 114.4% as filler content increased from 0 to 6% as observed from HG0 to HG6. Almost 55.48% increment in strength is seen from HG2 to HG4, while the flexural strength was marginally increased to 21.9% from HG4 to HG6. Among all fabricated samples, the higher and lower flexural strengths were displayed by HG6



(a) (b) (c)

Fig. 6 a Tensile stress–strain graph. **b** Ultimate tensile strength. **c** Tensile modulus of all samples



(a) (b)

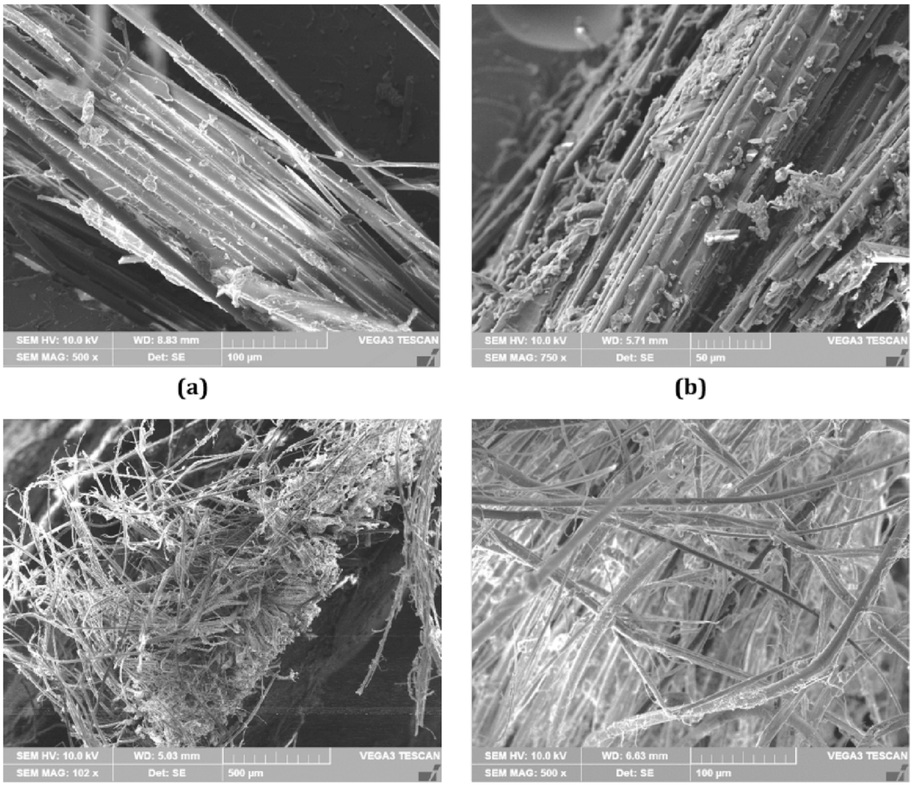
Fig. 7 a Flexural strength. **b** Flexural modulus of composite samples

and HG0 which was reported as 145 MPa and 311 MPa, respectively. Furthermore, flexural modulus for the sample HG6 was found to be higher as can be displayed in Fig. 7b. All the mechanical results are provided with error bars which represent the standard deviation. From the results obtained, it can be concluded that the improved interfacial force between fibre and matrix can be attained by inclusion of graphene particles which results in superior mechanical strength [31, 32]. In the present study, hybrid carbon/Kevlar fabric mat was utilized which can replace the individual mat usage and obtain significant improvement in mechanical properties of fibre-reinforced polymer composites.

The SEM images shown in figure resemble the brittle fracture of all composite samples. As the filler loading increased from 2 to 6%, graphene particles formed as continuous networks on the fibre surface as assessed from Fig. 8a, b. Due to this, the sample HG6 showed improved interfacial bonding among fibre/matrix/filler which significantly affected its mechanical strength. Besides, the images also reveal the uniform dispersion of filler particles in the composites due to ultra-sonication process during fabrication. Thus, agglomeration was not detected in the images. Figure 8c, d represents the fracture images of HG2 and HG6 subjected to tensile loading respectively. Due to lower filler content, surface of sample HG2 failed by weak interface bonding and fibre pull-out [33]. Along fibre direction, the uneven breakage occurred, while the fibre cracking lowered in the case of HG6 compared to HG2 due to more graphene particles present in the composite (see Fig. 8d).

Conclusions

Epoxy composites comprising four layers of hybrid carbon/Kevlar fabric mat with varying weight percentage of graphene particles were fabricated through lay-up lamination technique. Specimens were mechanically tested to understand their tensile and flexural strength. Based on results obtained, the following observations were summarized below.



(a) (b)

(c) (d)

Fig. 8 **a**–**d** SEM micrographs of fractured HG2 and HG6 samples

- Inclusion of graphene particles within hybrid carbon/Kevlar fabric significantly improved thermal stability and tensile and flexural strengths of composite laminates.
- Mechanical strength of composites increases with an increase in filler content due to the improved interfacial bonding between fibre/matrix/filler which resulted in greater load transfer.
- The sample HG6 with high filler loading exhibited 71% and 114.4% greater tensile and flexural strength respectively, as compared to unfilled HG0 composite.
- Thermal stability and hardness of HG6 were greater among all the specimens.
- SEM images reveal the uniform dispersion of graphene particles in the composite system. Besides, the samples have shown brittle fracture.

Abbreviations

FRPs	Fibre-reinforced composites
ASTM	American Society for Testing and Materials
TGA	Thermogravimetric analysis
UTM	Universal testing machine
SEM	Scanning electron microscope

Acknowledgements
Not applicable.

Authors' contributions
VBP, conceptualization, methodology, supervision, investigation, and writing — original draft. VB, formal analysis, data curation, visualization, and writing — review and editing. RD, data curation and writing — review and editing; PP, writing — review and editing; and AY, writing — review and editing.

Funding
The author(s) received no financial support for the research, authorship, and/or publication of this article.

Availability of data and materials
Data is available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 13 March 2024 Accepted: 4 May 2024

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