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Thermomechanical behavior of graphene nanoplatelets and bamboo micro filler incorporated epoxy hybrid composites

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Abstract

The present study is focused on the development of micro bamboo filler/epoxy hybrid composite with the incorporation of varied weight percentage of graphene nanoplatelet (GNPs). To check the effect of inclusion of dual fillers on the structural x-ray diffraction (XRD), morphological analysis by scanning electron microscope (SEM) and thermomechanical analysis (TMA) are carried out. The micro bamboo and GNPs filler in the epoxy polymer are incorporated to eradicate the problem associated with natural and synthetic fibers alignment, delamination, and anisotropic property in the thermoset composite materials. Results revealed that with the inclusion of graphene nanoplatelet with bamboo filler in epoxy composite improves the synergetic effect, which in turn increases the tensile, flexural, loss modulus and storage modulus of developed hybrid composite material. SEM analysis confirmed the proper distribution of fillers and their presence from XRD analysis. All fabricated hybrid composite displayed improved thermal conductivity value and a marginal increase in the corrosion rate. The overall result predicts that the improvement is quite better compared to neat or solo bamboo filler based epoxy composite. The improvement is ascribed due to the proper interfacial bonding or cross-link between micro bamboo filler/epoxy polymer with the addition of GNPs. Developed filler based hybrid composite may be utilized for the application of thermal interface material, circuit board, electronic packaging, etc.

1. Introduction

There is a constantly growing demand for innovative materials with improved properties to fulfill new challenging necessities. The inclusion of fiber/filler materials to polymer matrix is the usual practice for developing composite materials. Polymers have extended wider application areas in different branches of the industry due to their lightweight, nominal price and excellent corrosion resistance [1, 2]. Among various thermoset and thermoplastic polymers, thermoset epoxy resin possesses high mechanical properties, excellent thermal and dimensional stability. However, as epoxy polymers undergo the state of solidification, it becomes more brittle in nature [3, 4]. High brittleness is a matter of serious problem which can be minimized by incorporating natural or inorganic fiber/filler. The great performance of continuous natural and synthetic fiber reinforced in a polymer matrix is well known and established. However, these long fiber-based polymer composite have some drawbacks. Such as major problems like delamination which can be avoided by the inclusion of micro/nanofiller instead of fibers. These disadvantages often limit their area of application and create the requirement to develop the improvement of polymer composite materials.

Also, significant growing cognizance and concerns of greener and eco-friendly environment in humanity developed a deep interest in the utilization of natural filler and fiber [5]. Use of different recyclable and renewable reinforcement materials are encouraged such as plant leaves, crop, husk, jute, flax, kenaf, wood dust, and bamboo dust, etc, in spite of many efforts towards applying renewable and biodegradable polymer for industrial use, there is serious limitation identified in the thermomechanical properties. Since the last few years, most of the composite materials have been developed from natural and synthetic fibers [6, 7]. The major benefits
of natural fiber over synthetic fiber are eco-friendly, biodegradable, plentifully availability etc. Meanwhile, there are few shortfalls found such as higher hydrophilic nature due to the existence of hydroxyl groups, miserable compatibility with epoxy matrix, homogeneous distribution etc. But, the low price of natural filler/fiber and performance ratio at low weight in combination with environmental friendly nature become the major factor for the social acceptance of natural fibers in a huge volume in the research and material development area such as automobile, decorative and building construction [8]. The natural fibers such as jute, hemp, banana, bamboo, kenaf etc are introduced as incorporated material in the polymer matrix and these natural fiber-based developed composites have a many advantages such as higher stiffness, high modulus, and improved strength. Amid the various natural fiber/fillers, Bamboo is very versatile and an adequate amount is available in the northeast regions of India. Bamboo is a renewable natural resource due to its fast-growing and availability in many other countries, especially in South East Asia, with total bamboo forest area in the world approximately 22 million hectar. Bamboo is the fastest natural plant with a life cycle of nearly 3 to 4 years and it is also low in price compared to other wood resources [9]. The marketing of bamboo-based products and their manufacturing and development have increased rapidly. Hence, effective utilization of unwanted bamboo particulate is concentrated for developing micro bamboo filler based polymer composite, it appears as an opportunity to replace natural fiber for enhancing the properties of the materials [10]. Bamboo possesses wonderful mechanical properties compared to its mass due to the unique natural physical structure [11]. Bamboo filler becomes one of the finest natural filler for inclusion in the epoxy matrix [12]. This is also observed that composite developed from natural filler and epoxy matrix exhibit certain drawbacks, like poor binding between epoxy and natural filler, agglomeration problem at higher filler weight percentage and rise the moisture content.

The main constituents of bamboo are cellulose, hemicellulose, lignin and other residues possess strong hydrophilic nature. However, for developing stronger bond, hydrophobic properties of filler is most suitable for the epoxy matrix. Also, to improve their reinforcing effect in epoxy matrix composite, chemical treatment of raw bamboo filler is essential. Chemical treatments such as alkali, silane, benzoylation, acylation, isocyanates, permanganate and acid based treatment are mostly preferred of the natural filler and fiber [13, 14]. Polymer composite with natural filler inclusion does not show major enhancement in thermal and electrical properties. In order to accomplish a better thermomechanical property in polymer-based composite, various types of conductive fillers are added such as metal powder, carbon black, carbon nanotube, and natural graphite are used as inclusion fillers in an epoxy matrix. In the present work, GNPs are selected as potential alternative fillers as compared to other conductive fillers since GNPs are well-known for their superior strength and thermal properties. Developing a hybrid composite with both natural micro bamboo filler and high conductive GNPs filler is characterized for an initial attempt. This approach will help to produce a cost-effective and lightweight polymer hybrid composite. Improved thermomechanical properties of the hybrid composite may fulfill the mechanical strength along with improved heat transfer capability. The suitable application areas are like thermal interface materials, electronic chips, light-emitting diode, and conductive packaging. The literature study makes a clear confirmation that no study has been conducted for developing hybrid composite with micro-sized bamboo filler reinforced in the epoxy composite with varied wt% of GNPs as a conductive filler. In this study, an effort has been taken to fabricate a nano-sized conductive filler blended with natural filler in the epoxy polymer. The developed conductive hybrid composite is prepared by changing GNP's wt% from 0.1, 0.2, 0.4, 0.6, 0.8, 1 and fixed micro bamboo filler at 5 wt%. The effect of GNP's filler inclusion in bamboo/epoxy composite on structural, morphological and thermomechanical properties are examined, through XRD, SEM, TMA also corrosion and conductivity tests are included. In order to open a fresh platform, GNPs and micro bamboo filler are added into epoxy for developing hybrid composite.

2. Material and methods

The hybrid composite was developed by using waste bamboo powder extracted from Bambousa Balcooa collected from Bamboo and cane development institute (BCDI), India and GNPs are obtained from platonic nanotech private limited with purity >99%. The standard epoxy matrix has two parts with resin diglycidyl ether of bisphenol A (DGEBA) and hardener Triethylenetetramine (TETA). The bamboo particulate filler was thoroughly cleaned with distilled water for removing external impurities and then dried in an oven at a temperature of 50 °C for 10 h. This specific set of temperature and duration of drying time of bamboo filler were standard on the basis of consecutive experimentation. The processed bamboo dust was crushed into the small microparticle by using ball milling to obtain the particle size less than 75 μm. These small bamboo particles were allowed to pass through 75 to 63 micron test sieve.
2.1. Chemical reaction

It was well-identified that natural bamboo filler contains cellulose, hemicellulose, lignin, wax, and pentose structural rings with an attached hydroxyl group. Chemical treatment was carried out to accomplish the proper bonding between the epoxy resin and bamboo filler, and to abolish the oils, wax from the surface and depolymerizing cellulose filler for enhancing the thermomechanical properties. The mercerization reaction of bamboo particulates was carried out in 6 wt% of sodium hydroxide solution, in a cylindrical container. The container was placed on the magnetic stirrer for 8 h at 47°C and 850 rpm. Once the reaction was finished, the bamboo particulate solution was cleaned multiple times with distilled water and acetone till pH 7 was reached. Later the surface improved bamboo particulates were filtered and dried in the muffle furnace at 60°C for 6 h. Future filler particulates were stored in an air-sealed polythene pouch containing silica gel to reduce the moisture present.

The schematic diagram of a chemical reaction among NaOH salt and bamboo filler is shown in figure 1. The chemical treatment eliminates a definite amount of hemicellulose, lignin, wax, and oils covered on the outer layer of the filler cell wall. The basic chemical starts with the breakdown of the ionic bond of NaOH molecules into Na⁺ cations and OH⁻ anions, as a result of the opposite polarity with H₂O molecules. Subsequently, Na⁺ ions are attached to the bamboo filler particulates through covalent bonding. Treatment improves surface topography, the highly polarised filler surface enhance the filler matrix binding [15].

2.1.1. Fabrication of hybrid composite and test specimens

The micro bamboo and GNPs filler based hybrid composite specimen were developed by hand layup technique using silicon rubber moulds as per the sample dimension for a different kind of testing. Silicon oil was used as a liberating agent for the easy removal of the final hybrid composite sample from the mould cavity. The measured quantity of epoxy resin, hardener, treated bamboo, and GNPs were weighted using the electronic balance. The epoxy resin diglycidal ether of bisphenol A and hardener Triethylenetetraamine were blended in ration 10:1 by weight percentage and continuously mixed for 3 to 4 min. The NH₂ group presences in the TETA is responsible for the cross-linking mechanism where covalent bond are established with the carbon atoms of DGEBA, Graphene nanoplatelet and cellulose bamboo filler [16, 17]. Then, a measured quantity of GNPs and treated bamboo filler were added in the resin, followed by continuous mechanical stirring at 200 rpm for 5 to 8 min and sonicated for 1 h at 75 watt power. Then, the prepared homogeneous mixture was placed inside a round vacuum desiccator for degassing at 0.1 Torr vacuum pressure. After degasifying, hybrid mixture was poured into the silicon rubber mould and trapped air and extra materials were removed by using hand roller with mild pressure. Then, the mixture was left for the curing process at room temperature as recommended by the manufacturer. Afterwards, samples were removed from the mould cavity by applying little pressure and subjected to a different kind of mechanical and thermal testing. The specimens for tensile, flexural DMA, conductivity and corrosion tests were prepared using varied GNPs filler weight fraction of 0.2%, 0.4%, 0.6%, 0.8%, and 1%, and the treated micro bamboo filler was kept constant at 5 wt% for all the prepared specimens. Also, neat epoxy samples were prepared without any filler addition. Here onwards the neat sample has been named as BG0, BG0.2 means GNPs with 0.2 wt% and 5 wt% micro bamboo filler sample is noted BG0.2, similarly BG0.4, BG0.6, BG0.8, BG1 represent corresponding GNPs wt% at constant micro bamboo weight filler inclusion of 5 wt%.

3. Characterization

The crystallinity and amorphous phase of chemically treated and untreated natural bamboo filler were characterized using advance XRD setup. The deflection intensities were recorded on 2θ scale from 5° to 100° with step size 0.008° to identify the spectra of chemically treated and untreated filler. The wavelength of the x-ray source maintained at 1.5406 Å (CuKα radiation), operated at 40 mA, 45 kV. The void estimation was conducted as per ASTM D 2734 to examine the percentage of void presence for marketable acceptance. The tensile strength
4. Results and discussion

4.1. XRD characterization of chemically treated micro bamboo filler

The physical and mechanical characteristics of hybrid composite reinforced with natural micro bamboo filler and GNPs are influenced by stronger bonding development in the interface zone of reinforcement material and epoxy matrix. The surface modification of natural filler improves the magnitude of matrix and filler binding. This is possible by the enhancement of hydrophobicity, mobility, adherence of filler, and minimizing agglomeration rate. The chemical treatment with NaOH is preferred over other chemical treatments which is established based on acceptable results of natural fiber and filler, also this treatment preferably cost economical. The extraction of non-cellulosic constitutes from natural filler improves surface adhesion among filler and matrix and helps to extend the filler matrix bonding [18]. The XRD measurements are carried out for the confirmation of the purity and quality of filler material used in the epoxy matrix and also to evaluate the overall structural information. Figure 2. shows the XRD patterns of NaOH treated and untreated bamboo filler. GNPs filler is used as reinforcement material for achieving synergetic effect in the virgin matrix and micro bamboo filler. The chemical treatment of raw bamboo filler improves the crystallinity index of treated bamboo filler. The crystallinity of cellulose index ($Ic$), is calculated based on the Segal empirical technical approach [19].

$$Ic = \frac{I_{002}' - I_{am}}{I_{002}} \times 100$$ (1)

Where, $I_{002}'$ is the peak intensity corresponding to the plane cellulose miller indices plane (002), and $I_{am}$ is the minimum peak intensity corresponding to the amorphous plane (110). The improvement in the crystallinity of amorphous micro bamboo filler obtained as a result of partial extraction of wax, lignin and hemicellulose content after treatment. The two prominent well defined peaks are obtained at $2theta = 16.4^o$ and $22.4^o$. The higher peak intensity exhibited at plane $I_{002}$ because of the $\alpha$-cellulose. The overall increment in the crystallinity index after chemical treatment is around 23.76%. This is owing to elimination of protective material and possible recreation of stress in the cellulose chains as a consequence of the deduction of amorphous and pectin from the untreated micro bamboo filler [20].
4.2. Void analysis
The presence of higher percentage of void rises the amount of water absorption inside the hybrid composite material. To calculate the void percentage, both experimental density \( D_e \) and theoretical density \( D_t \) values of the composite are determined. The density of GNP, bamboo and resin are 0.17 g cm\(^{-3}\), 0.35 g cm\(^{-3}\) and 1.15 g cm\(^{-3}\) respectively. The experimental density value of the composite is determined by water immersion density measurement kit. The theoretical density of the composite is calculated using equation (2).

\[
D_t = \frac{R_r}{D_t} + \frac{R_b}{D_b} + \frac{R_g}{D_g} 
\]

where, \( R_r, R_b, R_g \) are weight percentage of resin, bamboo, and GNP respectively in the hybrid composite. \( D_r, D_b, D_g \) are the density of the resin, bamboo, and GNP respectively. Amount of void percentage can be calculated by using equation (3).

\[
V = \frac{D_t - D_e}{D_t} \times 100
\]

where, \( V \) is the volume % of void. The exhibited results of the void percentage for a different hybrid composite is displayed in the figure 3. The results show that the void percentage increases with the inclusion of filler in the epoxy matrix. The highest void percentage is obtained for the higher filler loaded sample specimen and minimum void observed in the case of neat epoxy composites. The void percentage for the GNP at 1 wt% specimen composite is around 2.35% and while for the neat epoxy specimen is 1.2%. Percentage of the void increases might be due to the formation of air bubble during the sample preparation. Also the different polarity nature of the micro bamboo, GNP filler and epoxy matrix boost up the void formation [21].

4.3. Dynamic mechanical properties
The variation of graphene weight percent in the bamboo epoxy composite under frequency and temperature is ascertained using DMA experiment. The results of storage modulus \( G' \) (MPa), Loss modulus \( G'' \) (MPa) and tan delta are evaluated. The temperature variation effect for neat epoxy as well as for BG0.2, BG0.4, BG0.6, BG0.8, BG1 hybrid composite sample is depicted in figures 4(a)–(c). The storage modulus value endorses valuable insight envisaging of the stiffness and molecular relaxation for all the prepared composite samples. Figure 4(a) shows the significant variation of \( G' \) value of neat epoxy and developed hybrid composite with treated bamboo micro filler and GNP. On examining, the variation of \( G' \) value is observed with temperature for micro bamboo filler and GNP based hybrid composite. In all the cases the \( G' \) values fall continuous with the increase in the temperature. Also, from the exhibited results it is clear that the \( G' \) remains broader in the glassy zone, as the hybrid composition is tightly closed in the low temperature region, the \( G' \) value remains in a higher range before entering the glass transition zone. However, in the temperature range from 65 °C to 95 °C the modulus path falls quickly, representing the leathery to the rubbery zone. As the temperature increases, the molecular movement of the hybrid composite takes place rapidly, this might be due to breakdown molecular linkage. Then slowly the \( G' \) value decreases in the rubbery zone. But, no significant change in the rubbery zone is observed for the developed
hybrid composite. The storage modulus curve exhibits the influence of higher percentage of GNPs in the micro bamboo filler based polymer composite. As the wt% of GNPs decrease, the storage modulus value minimizes. This drop in the storage modulus endorsed to the fact of addition of the GNPs percentage. The inclusion of GNPs enhances the interfacial attachment between micro bamboo filler and the epoxy matrix [22]. The $G'$ for neat epoxy is $\sim$ 1341 MPa, which has been improved to maximum value $\sim$ 1708 MPa for the BG1 prepared specimen. Hence demonstrating a significant improvement of $G'$ around 28% with increasing the graphene weight percentage. The higher $G'$ value of epoxy hybrid composite also reflects relatively higher thermomechanical behavior compared to neat epoxy sample.

Loss modulus ($G''$) values of the DMA result versus temperature for the developed hybrid composites are depicted in the figure 4(b). The graph representing a similar trend like storage modulus value for different filler weight percentages. The loss modulus value increases with the rise in the GNPs filler weight percentage. All the loss modulus path attain a maxima point for the highest dissipation of mechanical energy and reduce with increasing temperature, because of free molecular motion of polymer links. Interesting the $G''$ value for the maximum wt% of GNPs exhibited higher loss modulus value in comparison to neat polymer composite. This behavior is attributed due to the intensification of the internal friction that escalates energy dissipation [23].

The neat epoxy polymer and GNPs with 0.2 wt% displayed almost the same loss modulus value. However, the modulus curve falls down at a maximum temperature around 90 °C. For the hybrid composite with 1 wt% of GNPs though it exhibits maximum loss modulus value, meanwhile modulus path falls in the beginning when the temperature rises above 75 °C. It can be explained that in both the case of storage and loss modulus improved with the addition of higher GNPs filler wt%. The damping factor or tan delta for micro bamboo filler and GNPs hybrid composite is elucidated in the figure 4(c). The BG0.2 exhibited higher Tan delta value and BG1 specimen displayed lowest tan delta among all the developed hybrid composite samples. The tan delta value increases with the rise in the temperature and it reaches the highest level in the transition zone, followed by decrease in the rubbery zone for all the composites. As the wt% of GNPs increases, the damping factor value keep on dropping. Thus with the addition of GNPs filler, the tan delta peak becomes wider, the wider peak represents a higher time for relaxation of molecules because of inferior polymeric link movement. Significantly higher crosslinking density is developed for the hybrid composite due to better interfacial connection. The exhibited results are in line with various other DMA research findings [24–26].

### 4.4. Thermal conductivity of the hybrid composite

The experimental results of thermal conductivity values for the micro bamboo and GNPs filler incorporated hybrid composites are depicted in figure 5. The exhibited results clearly represent the improvement in the thermal conductivity of the hybrid composite materials. Improvement in the thermal conductivity value suggests the formation of conductive path inside hybrid composite material. The result exhibited that with the inclusion of GNPs filler thermal conductivity value of the hybrid composite continuously increased. The maximum thermal conductivity value obtained in the present study is 1.21 W mK$^{-1}$ with the inclusion of 1 wt% of GNPs filler in the micro bamboo epoxy composite. The improvement of thermal conductivity value is almost
Figure 4. a The significant variation of storage modulus. b Variation of loss modulus for the hybrid composite. c Damping factor variation for hybrid composite.
four times that of neat epoxy sample. These results are achieved because of the higher thermal conductive network, also the crystallinity of epoxy composite is increased with filler addition [27].

4.5. Mechanical behavior of hybrid composite

The mechanical behavior of developed hybrid is determined and the evaluation of the results of uniaxial tensile strength, elastic modulus at different crosshead speed are presented in figures 6(a)–(c). The ultimate tensile strength and elastic modulus of the material is widely accepted for providing the basic structural design information. The values of tensile strength and elastic modulus are assessed from the stress–strain graph developed during the uniaxial tensile test. The influence of GNPs filler variation and increase in crosshead speed help to examine the difference in the results of prepared hybrid composites. The inclusion of GNPs in the micro bamboo epoxy composite significantly improves the mechanical properties. With the reinforcement of varying GNPs wt% and fixed amount micro bamboo filler epoxy composite, the ultimate tensile strength value also improved up to 0.8 wt of GNPs. Further, as the GNPs percentage increases the downfall in the tensile result is observed. This enhancement in the result up to GB0.8 might be endorsed due to improved stress transfer potential in the epoxy matrix. But at 1 wt% GNPs the decrease in the result is exhibited due to increased filler agglomeration. Agglomeration development inside the composite minimizes the stress transfer from the epoxy matrix to filler materials and generate a higher stress concentration zone [28]. The maximum tensile strength obtained for GB0.8 specimen is 52.48 MPa and elastic modulus of 1.28 GPa. From the result, it is examined that variation of crosshead speed from 1 to 3 mm min⁻¹ does not contribute much change to the results.

The inclusion of hybrid filler in the epoxy matrix enhances the ultimate tensile strength and elastic modulus result, which helps to rise the deflection resistance of the material. Also, an increase in the crystallinity percentage of developed hybrid composite with the addition of micro bamboo filler and GNPs, reduces the amorphous zone. As the amorphous region of composite minimizes, which help to significantly improve the elastic modulus of the polymer composite [29].

The flexural behavior of the micro bamboo and GNPs filler epoxy–based hybrid composite specimen are tested in three point bending modes. The exhibited results of flexural strength and flexural modulus at different crosshead from 1 to 3 mm min⁻¹ are shown in figures 7(a)–(c). It is clear from the results that the addition of filler improves the flexural strength and flexural modulus of the hybrid composite. These trends of improvement in the flexural properties can be well understood by the interaction of micro bamboo and GNPs fillers that develop a good bond. The stronger bonding interaction is the major role for improving the load transfer capability between epoxy matrix and hybrid filler [30]. The experimental results of both tensile and flexural behavior of hybrid composite increase with the incorporation of dual filler, however GNPs filler percentage variation up to 0.8 wt percentage exhibit maximum improvement.

A similar trend of variation in the tensile and flexural properties are also reported for natural filler blended epoxy composite. The maximum value of flexural strength and flexural modulus for the developed hybrid composite is 56.8 MPa and 5.19 GPa respectively. The exhibited results for the prepared hybrid composite materials are much better than individual natural filler based polymer composite. The flexural modulus and

Figure 5. Thermal conductivity values of hybrid composite.
The flexural strength of the epoxy hybrid composites are increased by filler inclusion up to around 43% and 13% respectively.

4.6. Corrosion analysis

Corrosion resistance analysis of a material is significantly essential because it slowly damages the product by environmental chemical reaction. Products that are developed from a metal such as iron, aluminium, copper gets quickly corroded when exposed to moisture environment. The epoxy polymer is used for abating corrosion...
resistance. But, to understand the effect of corrosion behavior of the polymer composite after filler inclusion is essential.

In the present study, the corrosion rate of the hybrid composite is measured after immersing it in 3.5 wt% of NaCl and NaOH solution for 36 h. The corrosion rate of the developed hybrid composite with respect to varied filler wt% is shown in figure 8. The lowest corrosion rate is exhibited for the neat epoxy specimen which is approximately 0.00035 and 0.00186 mm/year in the NaOH and NaCl respectively. However, when the filler
percentage increases in the epoxy composite, corrosion rate rises slowly and the maximum corrosion rate achieved in the present work is 0.062 and 0.057 mm/year in the NaOH and NaCl aqueous solution. Slight rise in the corrosion rate of the hybrid composite might be due to increase in void and chemical reaction with GNPs fillers [31].

4.7. Micro bamboo and GNPs filler surface morphology

The characteristic of the morphology structure of the micro bamboo filler and GNPs is depicted in figure 9. At lower and higher magnification. It can be observed that a large amount of bamboo fillers are distributed randomly in the epoxy matrix. The superior GNPs nano-fillers interact in the gaps of micro bamboo filler for
enhancing the bonding strength and improving the properties of the developed composite material [32–35]. The shape and size of bamboo filler and GNPs are prominently visible from the SEM analysis of the fractured surface of the hybrid sample. The higher weight percentage bamboo filler is examined by optical micrograph image. Figure 10 shows the visualisation of micro sized bamboo filler in the composite material at 100 μm. The main objective of this study is to examine void formation and bond developed between filler and matrix material.

5. Conclusion

The recent study is focused to utilize waste natural fillers that are sufficiently available to us. Aim is to minimize various problems associated with the use of natural fiber in epoxy polymer. Micro-sized bamboo filler and GNPs are used here for developing a new hybrid composite material for enhancing the thermomechanical behavior. After a thorough examination on the developed hybrid composite subsequent conclusions are summarized below.

- Micro bamboo filler and GNPs reinforced epoxy hybrid composite exhibited enhanced thermal and mechanical properties. Chemical modification supported in the formation of stronger binding strength by altering its physical structure. In the meantime, GNPs filler helped in the development of the conductive path inside the polymer composite.
- Presence of nanofiller played a major role to minimize the crack generation and reduced brittleness character of the hybrid composite material
- Hybrid filler improved synergistic effect in the polymer composite which helps to raise the storage, loss modulus and damping factor of the composite. This also helps to increase the temperature range of the polymer material.
- Improvement in the thermal conductivity value was achieved for hybrid composite up to 1.21 W mK−1 from 0.25 W mK−1 with increasing the GNPs filler inclusion percentage.
- Mechanical properties such as tensile strength, flexural strength, elastic modulus and flexural modulus showed maximum values for developed GB0.8 hybrid composite.

The conclusion suggests that higher wt percentage of GNP can be attempted further for examining thermomechanical properties. Also, modification of natural filler is essential for improving crystallinity and morphological behavior.

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References

[1] Datsyuk V, Trotsenko S and Reich S 2013 Carbon-nanotube–polymer nanofibers with high thermal conductivity Carbon 52 605–8

[2] Zhang Y C, Dai K, Yang H, Liu X and Li Z M 2010 Anisotropically conductive polymer composites with a selective distribution of carbon black in an in situ microfibrillar reinforced blend Mater. Lett. 64 1459–62

[3] Zhang X, Sun H, Yang C, Zhang K, Yuan M M and Yang S 2013 Highly conductive polymer composites from room-temperature ionic liquid cured epoxy resin: effect of interphase layer on percolation conductance RSC Adv. 3 1916–21

[4] Luo B, Wang X, Zhao Q and Li L 2015 Synthesis, characterization and dielectric properties of surface functionalized ferroelectric ceramic/epoxy resin composites with high dielectric permittivity Compos. Sci. Technol. 112 1–7

[5] Lewandowski K, Piszczek K, Zachowiak S and Mirowski J 2016 Rheological properties of wood polymer composites at high shear rates Polym. Testing. 51 58–62

[6] Andrzejewski J, Tutak N and Szostak M 2016 Polypropylene composites obtained from self-reinforced hybrid fiber system J. Appl. Polym. Sci. 133 1–9

[7] Taszkiewicz A, Bledzki A K and Francisczak F 2013 Improving the mechanical performance of PLA composites with natural, man-made cellulose and glass fibers— a comparison to PP counterparts Polymery. 58 433–42

[8] Mittal V, Saini R and Sinha S 2016 Natural fiber–mediated epoxy composites—a review Compos B Eng. 99 425–35

[9] Gupta A and Kumar A 2008 Potential of bamboo in sustainable development Asia Pac. Bus. Rev. 4 100–7

[10] Li Z H and Kobayashi M 2004 Plantation future of bamboo in China J. For. Res. 15 233–42

[11] Tan T, Rabbar N, Allamleh SM, Kwofi S, Dismore D, Ghavami K and Soboyejo W O 2011 Mechanical properties of functionally graded hierarchical bamboo structures Acta Biomater. 7 3796–803

[12] Khuller H A, Bhat I U H, Jawaid M, Zaidon A, Herrman D and Hadzi Y S 2012 Bamboo fibre reinforced biocomposites: a review Mater. Des. 42 353–68

[13] Li X, Tabi L G and Panigrahi S 2007 Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review J. Polym. Environ. 15 25–33

[14] Gassan J and Bledzki A K 1999 Possibilities for improving the mechanical properties of jute/epoxy composites by alkali treatment of fibres Compos. Sci. Technol. 59 1303–9

[15] Bledzki A K, Fink H P and Specht K 2004 Unidirectional hemp and flax EP- and PP-composites: influence of defined fiber treatments J. Appl. Polym. Sci. 93 2150–6

[16] Safari S 2019 Investigation on effect of chemical composition of bio-fillers on filler/ matrix interaction and properties of particle reinforced composites using FTIR Compos B Eng. 166 21–30

[17] Kumar R, Kumar K, Bhowmik S and Sarkhel G 2019 Tailoring the performance of bamboo filler reinforced epoxy composite: insights into fracture properties and fracture mechanism J. Polym. Res. 26 1–15

[18] Segal L, Creely J I, Martin A E Jr and Conrad C M 1995 An empirical method for estimating the degree of crystallinity of native cellulose using the x-ray diffractometer Text. Res. J. 65 2986

[19] Junior A C, Barreto A C H, Roso D S, Maia F J N, Lomonaco D and Mazzetto S E 2015 Thermal and mechanical properties of biocomposites based on a cashew nut shell liquid matrix reinforced with bamboo fibers J. Compos. Mater. 49 2203–15

[20] Li Y, Jiang L, Xiong C and Peng W 2015 Effect of different surface treatment for bamboo fiber on the crystallization behavior and mechanical property of bamboo fiber/nanohydroxypatite/poly (lactic-co-glycolic) composite Ind. Eng. Chem. Res. 54 12017–24

[21] Fiore V, Scalici T, Vitale G and Valenza A 2014 Static and dynamic mechanical properties of Arundo Donax fillers–epoxy composites Mater. Des. 57 456–64

[22] Prolongo S G, Moriche R, Jiménez-Suárez A, Sánchez M and Urrea A 2014 Advantages and disadvantages of the addition of graphene nanoplatelets to epoxy resins Eur. Polym. J. 61 206–14

[23] Saba N, Paridah M T, Aband K and Ibrahim N A 2016 Dynamic mechanical properties of oil palm nano filler/kena/epoxy hybrid nanocomposites Constr. Build. Mater. 124 133–8

[24] Wang F, Drzal L T, Qin Y and Huang Z 2015 Mechanical properties and thermal conductivity of graphene nanoplatelet/epoxy composites J. Mater. Sci. 50 1082–93

[25] Chandrasekaran S, Seidel C and Schulte K 2013 Preparation and characterization of graphite nano-platelet (GNP)/epoxy nano-composite: mechanical, electrical and thermal properties Eur. Polym. J. 49 3878–88

[26] Jawaid M, Khuller H A, Hassan A, Dungani R and Hadiyane A 2013 Effect of jute fibre loading on tensile and dynamic mechanical properties of oil palm epoxy composites Compos Part B Eng. 45 619–24

[27] Wang S, Cheng Y, Wang R, Sun J and Gao L 2014 Highly thermal conductive copper nanofiber composites with ultralow loading: toward applications as thermal interface materials ACS Appl. Mater. Interfaces 6 6481–6

[28] Shokrieh M M, Ghoreishi S M, Esikhani M and Zhao Z 2014 Effects of graphene nanoplatelets and graphene nanosheets on fracture toughness of epoxy nanocomposites Fatigue Fract Eng. Mater. 37 1116–23

[29] Ndiaye D, Fanton E, Morlais-Therias S, Tidjani A and Gardette J L 2008 Durability of wood polymer composites: Part I. Influence of wood on the photochemical properties Compos. Sci. Technol. 68 2779–84

[30] Yusuf I T, Jimoh Y A and Salami W A 2016 An appropriate relationship between flexural strength and compressive strength of palm kernel shell concrete Alex Eng J. 55 1535–62

[31] Khan N W, Troconis B R and Frankel G S 2014 Effects of carbon nanotube content on adhesion strength and wear and corrosion resistance of epoxy composite coatings on AA2024-T3 Prog. Org. Coat. 77 72–80

[32] Kumar R, Bhowmik S and Kumar K 2017 Establishment and effect of constraint on different mechanical properties of bamboo filler reinforced epoxy composite Int. Polym. Proc. 32 308–15

[33] Bansal S A, Singh A P and Kumar S 2018 Synergistic effect of graphene and carbon nanotubes on mechanical and thermal performance of polystyrene Mater. Res. Express 507602

[34] Bansal S A, Singh A P, Kumar A, Kumar S, Kumar N and Goswamy J K 2018 Improved mechanical performance of bisphenol—a graphene–oxide nano–composites J. Compos. Mater. 52 2179–88

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[35] Kumar V, Chopra A, Arora S, Yadav S, Kumar S and Kaur I 2015 Amperometric sensing of urea using edge activated graphene nanoplatelets RSC Adv. 5 13278–84