Modified graphene nanoplatelet and epoxy/block copolymer-based nanocomposite: physical characteristic and EMI shielding studies

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Abstract In this research work, diglycidyl ether of bisphenol-A (DGEBA) and polystyrene-block-poly(ethylene-ran-butylene)-block-polystyrene (PSPEB) were blended and loaded with purified graphene nanoplatelet (GNP-P) and acid-functionalized graphene nanoplatelet (GNP-F). Solution mixing route was used for nanocomposite processing with diaminodiphenylmethane as a hardener. According to SEM, inclusion of functional GNP-F depicted fine morphology due to interfacial adhesion between functional nanofiller and blend. Sharp increase in ultimate tensile strength and toughness was observed for DGEBA/PSPEB/GNP-F 0.03–0.1 system, i.e. 60.4–64.5 MPa and 422.6–725.5 MPa, respectively. For 0.1 wt.% GNP-P loading, \( T_{\text{max}} \) was observed as 547 °C; whereas, GNP-F showed higher value of 568 °C. Glass transition temperature of acid functional system was also higher (258 °C) than purified one (229 °C). DGEBA/PSPEB/GNP-F 0.1 depicted semi-crystalline nature (12.5° and 19.1°). EMI shielding effectiveness of nanocomposite was sufficiently high in the range of ~17.9–20.07 dB, i.e. desired for aerospace applications. Moreover, introduction of 0.1 wt.% functional graphene nanoplatelet enhanced the electrical conductivity up to 0.14 cm-1.

Keywords DGEBA, Graphene nanoplatelet, Block copolymer, Toughness, \( T_{\text{max}} \), EMI shielding

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Introduction

To increase the mechanical properties, thermal stability, electrical conductivity, and other physical properties of polymer nanocomposite, various carbon-based nanofiller have been employed.1 Nanoscale carbon filler include fullerene, carbon nanotube, graphene, graphene nanoplatelet (GNP) carbon nanofiber, and carbon black. In specific, carbon-based nanofiller is active for enhancing the performance in electrical conduction of non-conductive polymer matrix.2 Geometric structure of GNP consist of stack of platelets, however, the number of atomic layers may differ. These features expressively change their aspect ratio and specific surface area.3 Higher specific surface area of nanofiller may result in van der Waals forces and \( n-n \) interaction, which generally causes difficulty in dispersion.4 The properties of polymer/GNP nanocomposite are a function of their chemical composition, nanofiller dispersion, geometry (shape and size), and interaction between nanofiller and matrix.5 GNP has been utilized as nanofiller in variety of polymers including epoxy resin,6,7 natural rubber, and other polymer matrices8,9 to improve their electrical, thermal, and mechanical properties. GNP is also a potential material for thermal management.

Consequently, polymer nanocomposite with graphene sheets have been considered for applications in several progressive areas such as electromagnetic shielding (SE), electronic components, capacitors, electrodes for rechargeable batteries, and actuators and sensors.10 For polymer/GNP nanocomposite of known composition, optimal properties have been achieved by altering nanofiller content in matrix, and also by adjusting interface interaction. In this regard, methods have been defined to functionalize GNP or tailor the surface chemistry of nanofiller. Two methods have been established for nanofiller surface functionalization, i.e. covalent and non-covalent methods. The covalent method includes grafting
of reactive modifiers on nanofiller surface. The non-covalent method utilizes physical interaction between nanofiller and modifier such as electrostatic interaction, hydrogen bonding, and van der Waals interaction. It is generally acknowledged that the surface modification of GNP improves its dispersion in polymer matrix.

Epoxy constitutes an important class of thermosetting polymers. It is utilized as a medium for fiber-reinforced composite and adhesives. Due to cross-linked network structure, epoxy polymers have been employed in structural manufacturing applications demanding high modulus, high temperature performance, and low moisture absorption. However, epoxy possesses some undesired properties as matrix, for example, brittleness and low fracture resistance. Accordingly, improvement in fracture toughness is demanded to enhance its potential in engineering applications. Properties of epoxy resin have been improved by inclusion of secondary phase particles in epoxy matrix. Inclusion of secondary phase particles or nanofiller may result in the improvement in glass transition temperature ($T_g$). Modified nanofiller have been found to improve $T_g$ of epoxy composite. Thermal conductivity of epoxy nanocomposite with graphene nanosheet has exhibited remarkable improvement. Similarly, thermal stability and electrical conductivity of epoxy/GNP nanocomposite has been explored. Electromagnetic interference (EMI) SE studies were also carried out on epoxy composites containing graphene nanosheet. However, epoxy/GNP composite have been rarely focused for EMI SE properties, because research on GNP-based polymer nanocomposite is a new area of research. Further, research developments are desirable to define its potential in technical applications.

In addition to epoxy resin, styrenic block copolymer has considerable scientific applications and technical interest. Properties of block copolymers rely on their self-assembling into ordered nano-sized structures and also interaction with other polymers. Research has shown that the amalgamation of nanoparticle into self-assembled block copolymers may greatly improve the electrical conductivity, mechanical strength, optical, and magnetic properties of materials. Nanocomposite of exfoliated graphite nanoplatelets and polystyrene-b-poly(ethylene-r-butylene)-b-polystyrene have been prepared by melt-compounding approach. Similarly, other block copolymers and GNP nanocomposite have been prepared. Research reports have been found on epoxy and block copolymer blends. Poly(ethylene oxide)–poly(ethylene-alt-propylene) diblock copolymer and poly(Bisphenol-A-co-epichlorohydrin) epoxy resin were blended and phase behavior was studied. However, epoxy blends with GNP have been rarely explored, because research on polymer/GNP nanocomposite is relatively new research area. Therefore, research efforts are needed to further identify and explore the potential of these nanocomposites.

We have adopted a novel approach of blending block copolymer with thermoset matrix. To the best of our knowledge, polystyrene-block-poly(ethylene-r-butylene)-block-polystyrene was blended for the first time with diglycidyl ether of bisphenol-A (DGEBA). However, few reports are available on epoxy and different block copolymer blends. The idea of blending basically arises from improving the physical properties of neat epoxy resin. The block copolymer may be physically or chemically miscible with the epoxy matrices. Consequently, the epoxy resin may form interfacial contact between the block copolymer and epoxy domains. These interfacial domains in epoxy/block copolymer blend may control the morphology and final material properties. Moreover, the epoxy and block copolymer ratio is an important parameter to control the blend microstructure and properties. When hardener is added to epoxy/block copolymer blend system, epoxy cures and the system may retain the composite nanostructure. In this way, the macrophase separation between the block copolymer and epoxy may be avoided, without deteriorating the material properties. Blend of epoxy matrix with block copolymer; thus, possess improved physical properties compared with the neat epoxy (brittle, poor mechanical properties) and rubbery copolymer. The epoxy/poly(styrene-block-poly(ethylene-r-butylene)-block-polystyrene blend (DGEBA/PSPEB) was loaded with purified graphene nanoplatelet (GNP-P) and acid functional graphene nanoplatelet (GNP-F) in various weight ratios. Solution mixing route was employed to prepare the desired nanocomposite films. Subsequently, structural and physical properties were investigated by thermogravimetric analysis (TGA), Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), differential scanning calorimetry (DSC), X-ray diffraction (XRD), and EMI SE measurement.

### Experimental

#### Chemicals

GNP (nanopowder), DGEBA (≥95.0%), polystyrene-block-poly(ethylene-r-butylene)-block-polystyrene (PSPEB, $M_n \sim 118,000$), 3,4-diamino-diphenylmethane (95%), tetrahydrofuran (THF, ≥99.9%), sulfuric acid ($\text{H}_2\text{SO}_4$, 99.99%), nitric acid ($\text{HNO}_3$, 70%), and hydrochloric acid ($\text{HCl}$, 37%) were obtained from Aldrich (St. Louis, USA).

#### Instrumentation

FTIR spectra were recorded using Excalibur Series FTIR Spectrometer, Model No. FTSW 300 MX manufactured by BIO-RAD. For phase morphological studies, samples were cryogenically fractured in liquid nitrogen and the morphology was investigated by FEI Nova 230 field emission scanning electron microscope (FE-SEM). Transmission electron microscopy (TEM) was conducted with a JEOL JEM 2100F TEM. The sample was prepared with a Leica UC-6 ultramicrotome having Diatome diamond knife at room temperature. Stress–strain behavior was examined using universal testing machine (Instron 4466) with a strain rate of 2 mm/min at 25 °C according to ASTM D638 standard method. Sample dimension were $50 \times 11 \times 1 \pm 0.01$ mm$^3$. Thermal stability was determined by NETZSCH TGA, model no. TG 209 F3, using 5 mg of sample in Al$_2$O$_3$ crucible (0–800 °C) at heating rate of 10 °C/min under nitrogen flow rate of 30 mL/min. DSC was performed by Perkin-Elmer Pyris 1 DSC (Boston, MA, USA) with 5 mg of samples at heating rate of 10 °C/min under nitrogen. XRD patterns were obtained at room temperature on X-ray diffractometer (3040/60 X’pert PRO) using Ni-filtered Cu Ka radiation (40 kV, 30 mA). For EMI SE
characterization, rectangular samples (5 cm$^2$) were prepared by compression molding using Carver hot press at 200 °C under 5 T pressure for 10 min. For EMI SE characterization in the X-band (8.2–12.4 GHz) frequency, ENA series network analyzer (Model E5071C) connected with a WR-90 rectangular waveguide was used. The electrical conductivity of thin films was measured at room temperature and ambient atmosphere using the four-point method (Keithley 2401).

Purification and acid-functionalization of graphene nanoplatelet (GNP-F)
Prior to acid functionalization, 1 g GNP was refluxed in 300 mL of HCl for 3 h (70 °C). After reflux, mixture was poured in 300 mL of deionized water and kept for 24 h. The mixture was filtered and washed several times with deionized water to attain neutral pH. The GNP-P was dried at 100 °C for 3 h.

One gram of GNP was refluxed in a mixture of H$_2$SO$_4$ (8 M) and HNO$_3$ (3 M) in the ratio 3:1 for 6 h (70 °C). After reflux, the mixture was poured in 500 mL of deionized water and filtered. The product was washed several times with deionized water to achieve neutral pH. After the maintenance of pH, GNP-F was dried in oven at 100 °C (3 h).

Preparation of DGEBA film
Two grams of DGEBA were stirred in 2 mL of THF for 0.2 h. The amine-hardener (10 wt.% of epoxy) was added in DGEBA mixture and stirred for 0.5 h. The mixture was poured in Teflon Petri-dish and left for overnight at room temperature under vacuum.

Preparation of epoxy/polystyrene-block-poly(ethylene-ran-butylene)-block-polystyrene/ purified graphene nanoplatelet nanocomposite (DGEBA/PSPEB/GNP-P)
Desired amount of GNP-P (0.01–0.3 g) was sonicated in 2 mL of THF for 1 h. Digital ultrasonic bath with energy and frequency of 60 W and 40 kHz was used. Then 0.01 g of PSPEB was separately dissolved in 2 mL of THF. A separate solution of 2 g of DGEBA was also prepared in 2 mL of THF. DGEBA and PSPEB solutions were first mixed and stirred for 0.5 h. Then the GNP-P dispersion was added to the blend mixture and stirred for 0.5 h. Finally, the hardener was added (epoxy/hardener ratio 1:0.25) and film was cast in Teflon Petri-dish at room temperature. The solution was poured in Teflon Petri-dish and left for 24 h under vacuum.

Preparation of epoxy/polystyrene-block-poly(ethylene-ran-butylene)-block-polystyrene/ acid-functional graphene nanoplatelet nanocomposite (DGEBA/PSPEB/GNP-F)
Similar to the procedure mentioned in Section Preparation of epoxy/polystyrene-block-poly(ethylene-ran-butylene)-block-polystyrene/ purified graphene nanoplatelet nanocomposite (DGEBA/PSPEB/GNP-P), desired amount of GNP-F (0.01–0.3 g) was dispersed in 2 mL of THF for 1 h. Then 0.01 g of PSPEB was dissolved in 2 mL of THF. Two grams of DGEBA were dissolved in 2 mL of THF. DGEBA and PSPEB solutions were first mixed and stirred for 0.5 h. Then the GNP-F dispersion was added to the blend mixture. After the addition of hardener (epoxy/hardener ratio 1:0.25), the films were cast in Teflon Petri-dishes under vacuum at room temperature. The photographic images of DGEBA and nanocomposite films are displayed in Figure 1 and sample composition is given in Table 1.

Figure 1 Photographic images of (A) DGEBA; (B) DGEBA/PSPEB; (C) DGEBA/PSPEB/GNP-P 0.01; (D) DGEBA/PSPEB/GNP-P 0.1; (E) DGEBA/PSPEB/GNP-F 0.01; and (F) DGEBA/PSPEB/GNP-F 0.1
Table 1 Sample designation used for the nanocomposite prepared in this study

| Name  | Code                     | Epoxy (g) | PSPEB (g) | GNP (g) |
|-------|--------------------------|-----------|-----------|---------|
| DGEBA | 2                        | 0         | 0         |         |
| DGEBA | 2                        | 0.01      | –         | 0.01    |
| DGEBA | 2                        | –         | 0.03      |         |
| DGEBA | 2                        | –         | 0.05      |         |
| DGEBA | 2                        | –         | 0.1       |         |
| DGEBA | 2                        | –         | 0.3       |         |
| DGEBA | 2                        | 0.01      | 0.01      |         |
| DGEBA | 2                        | 0.01      | 0.03      |         |
| DGEBA | 2                        | 0.01      | 0.05      |         |
| DGEBA | 2                        | 0.01      | 0.1       |         |
| DGEBA | 2                        | 0.01      | 0.3       |         |

Result and discussion

FTIR analysis

Functional characteristics of epoxy resin, blend, and nanocomposite were studied using FTIR spectroscopic analysis in the range of 500–4000 cm⁻¹. FTIR spectrum of cured DGEBA is shown in Figure 2(A). Opening of oxirane ring of DGEBA by amine hardener was confirmed by the presence of a broad peak at 3472 cm⁻¹ due to O–H stretching vibration. The peaks at 2874 and 2959 cm⁻¹ show symmetric and asymmetric C–H stretching vibrations, whereas peak at 2065 cm⁻¹ represents sp² C–H bending vibrations. The peak at 1474 cm⁻¹ was due to C–N stretching vibration of aliphatic C–N bond in oxirane ring peak also appeared at 852 cm⁻¹. Figure 2(B) shows the blend formation of DGEBA and PSPEB matrices. A broad band centered at 3460 cm⁻¹ appeared due to O–H stretching vibration, i.e. analogous to epoxy spectrum. However, the peak was lowered by 14 cm⁻¹ owing to physical interaction between the blend components. The distinctive peak at 2950 cm⁻¹ shows C–H bond stretching, while peak at 2073 reveals sp² C–H bending. The peaks at 1614 and 1514 cm⁻¹ correspond to C=C stretching vibrations of aromatic rings, also present in DGEBA spectrum. The phenyl C–O stretching vibration was seen at 1219 cm⁻¹, while peak at 1255 cm⁻¹ was due to aliphatic C–O stretching vibration. The meta-substituted aromatic ring of PSPEB was also found at 770 cm⁻¹. Figure 3(A) illustrates FTIR spectrum of DGEBA/PSPEB/GNP-P 0.1 nanocomposite. An important feature was the presence of broad band at 3480 cm⁻¹ due to O–H stretch. The peaks appearing at 2869 and 2957 cm⁻¹ show symmetric and asymmetric C–H stretching vibrations. In DGEBA/PSPEB/GNP-P 0.1 nanocomposite, peak at 1519 shows C=C sp² character. The peak at 1267 cm⁻¹ represents stretching vibration of aliphatic C–O bond, while phenyl C–O bond was appeared at 1132 cm⁻¹ for DGEBA. The peak at 963 cm⁻¹ exhibits C–O–C bond of oxirane ring, and peak at 839 cm⁻¹ was due to para-disubstituted groups of PSPEB. The asymmetric peak of alkyl group appeared at 2957 cm⁻¹. Figure 3(B) shows peak at 3463 cm⁻¹ due to O–H stretching vibration of DGEBA/PSPEB/GNP-P 0.1. The lowering of hydroxyl peak by 17 cm⁻¹ (compared with purified system) has indicated the formation of strong interaction between acid functional GNP and epoxy. The peak at 1521 cm⁻¹ represents stretching vibration of aromatic ring of matrix. Moreover, the peak at 1614 cm⁻¹ presents N–H bending vibration. Here, again the aliphatic and aromatic C–O bonds appeared at 1129 and 1262 cm⁻¹. Lowering of C–O bond also indicated the existence of secondary bond interaction between functional nanofiller and matrix. The characteristic absorption peak at 1681 cm⁻¹ arise due to carbonyl C=O of acid-functionalized GNP-P. The peak at 863 cm⁻¹ presents C–O–C bond of oxirane ring.
to purified one. The fact was obvious from high-resolution images. Figure 5(C) and (D) has shown the formation of gyroid pattern in the blends due to chemical bonding between the nanofiller and blend components. To study the nanofiller nature of GNP, TEM micrographs of nanocomposite have also been obtained (Figure 6). The micrographs have shown the dispersion of tiny polymer-coated nanoplatelets.

**Mechanical features**

Table 2 lists the tensile data of neat DGEBA/PSPEB blend and DGEBA/PSPEB/GNP nanocomposite. Ultimate tensile strength, elongation at break, and toughness, which are sensitive to load transfer between the phases, were used to monitor the consistency between the phases. Incorporation of purified GNP noticeably enhanced the tensile strength as compared to the neat matrix. Maximum strength of DGEBA/PSPEB/GNP-P was increased from 50.2 to 53.4 MPa with 0.03–0.1 wt.% nanofiller addition, relative to the blend (33.1 MPa). Increasing the functional GNP content from 0.03 to 0.1 wt.% further enhanced the ultimate tensile strength from 60.4 to 64.5 MPa (Figure 7). This can be elucidated based on the increased interfacial interaction between functional nanofiller and blend component. Higher values of the elongation at break were found for the blend, i.e. 19.9%. The elongation at break was decreased to 11.4% with 0.1 wt.% GNP-P. Later, significant decrease was observed in this property for DGEBA/PSPEB/GNP-F 0.1 (8.99%). Generally, better compatibilized polymer nanocomposite systems are tough. The DGEBA/PSPEB blend had toughness of 203.2 MPa. Toughness of DGEBA/PSPEB/GNP-P 0.03–0.1 was increased in the range of 267.3–312.7. Sharp increase in toughness was observed for DGEBA/PSPEB/GNP-F 0.03–0.1 system. The nanocomposite with 0.1 wt.% functional GNP has improved value of toughness, i.e. 725.5 MPa (Figure 8). The toughness result confirmed an increase in rigidity and presence of strong secondary interaction between the matrix and functional nanofiller.

**Thermogravimetric analysis**

Thermal behavior of blend and purified and acid functional GNP-based nanocomposite was studied using TGA (Table 3). The thermograms of DGEBA/PSPEB depicted two-step thermal decomposition. Initial decomposition temperature ($T_0$) and maximum weight loss temperature ($T_{max}$) were studied from the thermograms. The maximum weight loss or decomposition temperature was defined from the derivative thermogravimetric curve (DTG). In literature, the DTG peak points to the main decomposition of the composite structure. This temperature is often referred as maximum decomposition temperature ($T_D$) of DGEBA/PSPEB was around 338 °C, where the $T_{max}$ was found at 540 °C (Figure 9(A)). The initial weight loss was due to the breakdown of interaction between two polymers in the blend, whereas maximum decomposition involved breakdown of the polymer backbone. Addition of purified GNP enhanced the decomposition temperature of DGEBA/PSPEB/GNP-P 0.01–0.1 series. Addition of 0.01 wt.% GNP-P increased the $T_D$ and $T_{max}$ up to 343 and 542 °C, respectively. Further increase was observed up to the addition of 0.1 wt. % GNP-P in DGEBA (Figure 9(B)). In this case, the $T_D$ and $T_{max}$ were observed at 350 and 547 °C.
respectively. Though, further nanofiller addition (0.3 wt.%) decreased the thermal properties. Addition of acid-functionalized GNP-F was found to improve the thermal stability of nanocomposite. Consequently, the maximum thermal properties were attained for DGEBA/PSPEB/GNP-F with 0.1 wt.% nanofiller. The thermogram of DGEBA/PSPEB with 0.1 wt. % GNP-F is given in Figure 9(C). The incorporation of acid-functionalized nanofiller had significant impact on decomposition temperature, so improvement in thermal stability was observed. DGEBA/PSPEB/GNP-F 0.1 revealed higher values of \( T_0 \), and \( T_{\text{max}} \) around 355 and 568 °C, respectively. Here again, increasing the nanofiller content to 0.3 wt.% slightly decreased the thermal properties. This effect was probably due to the nanofiller aggregation, as evident from the micrograph of DGEBA/PSPEB/GNP-F 0.3 (Figure 5(E)). Similarly, purified GNP composite at higher loading was found to be aggregated (Figure 4(D)). Another important observation was change in the residual mass or char yield of nanocomposite. Char yield of DGEBA/PSPEB blend was found as 20%. Interestingly, the char yield was found to increase significantly with the GNP addition. For DGEBA/PSPEB/GNP-P 0.01–0.3, the char yield was increased in the range of 38–43%. The residual mass was further increased to 47% in the case of DGEBA/PSPEB/GNP-F 0.1. Increase in char residue of nanocomposite was a clear indication of increasing thermal stability with nanofiller addition. DSC technique was employed to study the glass transition temperature \( (T_g) \) of nanocomposite. DSC thermograms of DGEBA/PSPEB, DGEBA/PSPEB/GNP-P 0.1, and DGEBA/PSPEB/GNP-F 0.1 nanocomposite are shown in Figure 10. The \( T_g \) of DGEBA/PSPEB was 219 °C, which showed better compatibility of the blend components compared with the neat DGEBA (196 °C). The glass transition temperature of DGEBA/PSPEB/GNP 0.01–0.1 was found to improve with nanofiller loading. \( T_g \) for DGEBA/PSPEB with 0.1 wt.% GNP-P nanocomposite was observed at 229 °C. The increase in transition temperature was because of the GNP addition, which gives rigidity to the blended polymers. Moreover, the results depict that the inclusion of acid functional GNP-F in DGEBS/PSPEB blend enhanced the \( T_g \) values significantly up to 258 °C (Figure 10(C)). The increase in glass transition indicated better interaction between epoxy, copolymer, and functional nanofiller. Beyond 0.1 wt.% GNP-P/GNP-F loading, the glass transition was found to decrease because of the meager nanofiller dispersion in the matrix.

**XRD analysis**

XRD patterns of DGEBA and DGEBA/PSPEB are displayed in Figure 11. A broad peak was observed at \( 2\theta = 19.07^\circ \) due to the amorphous nature of polymer (Figure 11(A)). Almost similar pattern was observed in the diffractogram of DGEBA/PSPEB. A broad peak was observed at \( 2\theta = 19.99^\circ \) (Figure 11(B)). The structure of DGEBA/PSPEB/GNP-P was also studied (Figure 12(A)). Presence of a broad peak at \( 2\theta = 19.16^\circ \) depicted amorphous nature of the nanocomposite. An additional peak at \( 2\theta = 12.43^\circ \) indicated the presence of graphene nanofiller. This peak also pointed to the formation of GNP-based nanocomposite. Moreover, this peak was absent in case of DGEBA/PSPEB blend. The diffractogram for acid functional nanofiller loaded blend matrix is shown in Figure 12(B). Peak for acid-functionalized GNP was observed at 12.51°. While, the broad amorphous halo at 19.5° depicted amorphous nature of nanocomposite.
Figure 5  FESEM images of DGEBA/PSPEB/GNP-F 0.1 at (A) 100 μm; (B) 50 μm; (C) 1 μm; (D) 0.5 μm; and (E) DGEBA/PSPEB/GNP-F 0.3 at 0.5 μm

Figure 6  TEM images of (A) DGEBA/PSPEB/GNP-P 0.1 and (B) DGEBA/PSPEB/GNP-F 0.1
The SE effectiveness of neat blend was measured to be 3.65–3.76 dB. The effectiveness of DGEBA/PSPEB/GNP-P 0.1 was increased from 10.7 to 11.9 dB. The SE effectiveness was further improved in the range of 17.9–20.07 dB for DGEBA/PSPEB/GNP-F 0.1 nanocomposite. The increment in EMI SE effectiveness was attributed to the formation of conducting interconnected GNP-F network. Nevertheless, SE effectiveness of the blend and nanocomposite was found to be autonomous of frequency in the measured frequency region. Due to conducting nature as well as high aspect ratio, nanofiller act as interconnecting bridge between matrix and nanofiller. Introduction of GNP enhanced the electrical properties by facilitating the charge transfer process between the two components, i.e. nanofiller and matrix (Figure 16). This increases the coherence or coupling between the chains and leads to enhancement of EMI SE effectiveness over the frequency range of 8.2–12.4 GHz. The SE effectiveness of neat blend was measured to be 3.65–3.76 dB. The effectiveness of DGEBA/PSPEB/GNP-P 0.1 was increased from 10.7 to 11.9 dB. The SE effectiveness was further improved in the range of 17.9–20.07 dB for DGEBA/PSPEB/GNP-F 0.1 nanocomposite. The increment in EMI SE effectiveness was attributed to the formation of conducting interconnected GNP-F network. Nevertheless, SE effectiveness of the blend and nanocomposite was found to be autonomous of frequency in the measured frequency region. Due to conducting nature as well as high aspect ratio, nanofiller act as interconnecting bridge between matrix and nanofiller. Introduction of GNP enhanced the electrical properties by facilitating the charge transfer process between the two components, i.e. nanofiller and matrix (Figure 16). This increases the coherence or coupling between the chains and leads to enhancement of EMI SE effectiveness over the frequency range of 8.2–12.4 GHz. The SE effectiveness of neat blend was measured to be 3.65–3.76 dB. The effectiveness of DGEBA/PSPEB/GNP-P 0.1 was increased from 10.7 to 11.9 dB. The SE effectiveness was further improved in the range of 17.9–20.07 dB for DGEBA/PSPEB/GNP-F 0.1 nanocomposite. The increment in EMI SE effectiveness was attributed to the formation of conducting interconnected GNP-F network. Nevertheless, SE effectiveness of the blend and nanocomposite was found to be autonomous of frequency in the measured frequency region. Due to conducting nature as well as high aspect ratio, nanofiller act as interconnecting bridge between matrix and nanofiller. Introduction of GNP enhanced the electrical properties by facilitating the charge transfer process between the two components, i.e. nanofiller and matrix (Figure 16). This increases the coherence or coupling between the chains and leads to enhancement of EMI SE effectiveness over the frequency range of 8.2–12.4 GHz. The SE effectiveness of neat blend was measured to be 3.65–3.76 dB. The effectiveness of DGEBA/PSPEB/GNP-P 0.1 was increased from 10.7 to 11.9 dB. The SE effectiveness was further improved in the range of 17.9–20.07 dB for DGEBA/PSPEB/GNP-F 0.1 nanocomposite. The increment in EMI SE effectiveness was attributed to the formation of conducting interconnected GNP-F network. Nevertheless, SE effectiveness of the blend and nanocomposite was found to be autonomous of frequency in the measured frequency region. Due to conducting nature as well as high aspect ratio, nanofiller act as interconnecting bridge between matrix and nanofiller. Introduction of GNP enhanced the electrical properties by facilitating the charge transfer process between the two components, i.e. nanofiller and matrix (Figure 16). This increases the coherence or coupling between the chains and leads to enhancement of EMI SE effectiveness over the frequency range of 8.2–12.4 GHz. The SE effectiveness of neat blend was measured to be 3.65–3.76 dB. The effectiveness of DGEBA/PSPEB/GNP-P 0.1 was increased from 10.7 to 11.9 dB. The SE effectiveness was further improved in the range of 17.9–20.07 dB for DGEBA/PSPEB/GNP-F 0.1 nanocomposite. The increment in EMI SE effectiveness was attributed to the formation of conducting interconnected GNP-F network. Nevertheless, SE effectiveness of the blend and nanocomposite was found to be autonomous of frequency in the measured frequency region. Due to conducting nature as well as high aspect ratio, nanofiller act as interconnecting bridge between matrix and nanofiller. Introduction of GNP enhanced the electrical properties by facilitating the charge transfer process between the two components, i.e. nanofiller and matrix (Figure 16). This increases the coherence or coupling between the chains and leads to enhancement of...
Figure 9  TGA thermograms of (A) DGEBA/PSPEB; (B) DGEBA/PSPEB/GNP-P 0.1; and (C) DGEBA/PSPEB/GNP-F 0.1

Figure 10  DSC thermograms of (A) DGEBA/PSPEB; (B) DGEBA/PSPEB/GNP-P 0.1; and (C) DGEBA/PSPEB/GNP-F 0.1

Figure 11  X-ray diffractograms of (A) DGEBA and (B) DGEBA/PSPEB

Figure 12  X-ray diffractograms of (A) DGEBA/PSPEB/GNP-P and (B) DGEBA/PSPEB/GNP-F

Figure 13  Real part $\varepsilon'$ of permittivity of (A) DGEBA/PSPEB; (B) DGEBA/PSPEB/GNP-P 0.1; and (C) DGEBA/PSPEB/GNP-F 0.1

Figure 14  Imaginary part $\varepsilon''$ of permittivity of (A) DGEBA/PSPEB; (B) DGEBA/PSPEB/GNP-P 0.1; and (C) DGEBA/PSPEB/GNP-F 0.1
we have achieved the effectiveness of 20.07 dB with just the epoxy/graphene composite was found as 21 dB. However, Liang et al. have studied the EMI SE effectiveness of 15 wt.% of epoxy/graphene composite over a frequency range of 8.2–12.4 GHz (X-band). EMI SE effectiveness of 15 wt.% epoxy/graphene composite was found as 21 dB. However, we have achieved the effectiveness of 20.07 dB with just the addition of 0.1 wt.% functional GNP in DGEBA/PSPEB/GNP-F 0.1. EMI SE results combined with the advantages of low filler consumption, indicated that the novel composites can be commercially used as effective and lightweight SE materials for electromagnetic radiation.

**Conclusion**

In this research report, nanocomposite based on GNP has been fabricated by solution-processing route. The purified and GNP-F were used as nanofiller in epoxy and block copolymer blend matrix, i.e. DGEBA/PSPEB. Addition of acid functional GNP-F in blend matrix improved the morphological, thermal, and EMI SE properties of resulting nanocomposite. In comparison to GNP-P, remarkable dispersion and patterned morphology was achieved in the case of GNP-F. The interaction of microwave radiations with purified and acid functional GNP nanofiller attenuated electromagnetic energy and contributed to microwave absorption. The functional nanocomposite revealed fine EMI SE capability, so have potential for development of high-performance EMI SE materials. In other words, employment of functional GNP nanofiller enhanced the perspective relevance of DGEBA/PSPEB/GNP in several technical fields.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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