



Studies on toughened polycarbonate/multiwalled carbon nanotubes nanocomposites



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ARTICLE INFO

Article history:

Received 30 January 2017

Received in revised form

23 March 2017

Accepted 12 May 2017

Available online 13 May 2017

Keywords:

Polymer-matrix composites

Electrical properties

Mechanical testing

Injection moulding

ABSTRACT

The electrically conducting nanocomposites (NCs) of toughened polycarbonate (PC) fabricated by using melt blending method with different loadings of multiwalled carbon nanotube (MWCNTs) ranging from 0.25 to 10 phr were studied in this paper. Thus prepared NCs were characterized for morphology (scanning electron microscopy, transmission electron microscopy, Raman spectroscopy and X-ray diffraction), mechanical properties, thermal property, electrical conductivity (using two probe method) and electromagnetic interference shielding effectiveness (using vector network analyzer). The impact strength of toughened PC prepared by blending PC with 5 wt% of ethylene methyl acrylate (EMA) copolymer having impact strength 318 J/m i.e. 381% improvement as compared to neat PC was further increased to 19% (378 J/m) after 1 phr addition of MWCNTs. Maximum tensile strength and modulus of PC/EMA-MWCNT NCs (about 39 and 60% increase respectively as compare to PC/EMA blend) was achieved at the loading of 10 phr MWCNT. An electrical percolation threshold (p_c) occurred at 1 phr of MWCNTs and higher electrical conductivity value about $1.56 \times 10^{-3} \text{ S cm}^{-1}$ was attained for PC/EMA (95/5) having 10 phr of MWCNTs. Maximum EMI shielding effectiveness of toughened PC having 10 phr of MWCNTs was observed as $\sim -26 \text{ dB}$ in X-band with samples of 3 mm thickness.

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1. Introduction

The study of carbon nanotubes (CNTs) based polymer nanocomposites (NCs) has attracted substantial attention in industrial and academic field over the last few years [1–3] due to the extraordinary properties of CNTs such as mechanical properties (elastic modulus $\sim 1 \text{ TPa}$) [4], electrical conductivity ($10^4\text{--}10^6 \text{ S cm}^{-1}$) [5] and thermal conductivity (3000–6000 W/mK) [6]. The CNT-based thermoplastic (polypropylene, polyethylene, poly(ether ketone), polycarbonate etc.) NCs are reported in literature [7–10]. NCs exhibit significant improvements in electrical conductivity, mechanical and physical properties due to the high aspect ratio of CNTs. Electrically conducting CNTs filled polymeric materials having extensive commercial applications are used in different fields such as electronics, aerospace, military, medical applications including flexible electronics, high strength fibers, electromagnetic interference (EMI) shielding, electrostatic

dissipation, biomolecular sensors etc. [8,11–14].

PC is extensively used engineering thermoplastic in different fields such as aeronautical and automobile applications due to its good mechanical and thermal properties [15], transparency, high heat distortion temperature, flame retardance and high dart impact strength [16–18]. However, PC has some drawbacks such as poor processability, poor solvent resistance, non-conducting polymer and high degree of notch sensitivity [19]. The toughness is not retained in thick and sharp notched specimens of PC [20,21]. Due to the high degree of notch sensitivity, PC shows the tragic reduction in Izod impact strength of notched specimens. PC toughening has been reported by several authors using different elastomers such as acrylonitrile butadiene styrene (ABS) [22], poly(ethylene terephthalate) (PET) [23], polyethylene (PE) [24], etc. In our previous work, the preparation of toughened PC with improved notched impact strength using ethylene methyl acrylate (EMA) copolymer has been reported [25].

The incorporation of MWCNTs in PC matrix changes the tough matrix (ductile failure) to a brittle failure [26,27]. This problem is solved by the addition of elastomeric materials to PC matrix

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[28–30]. Elastomer modified PC/CNT NCs has been reported in the literature [31–43]. Sun et al. [31] explored the effect of acrylonitrile butadiene styrene (ABS) on selective localization of MWCNT in PC/ABS blend and electrical resistivity of NCs. MWCNTs have been added into PC/styrene-acrylonitrile (SAN) copolymer and PC/styrene-butadiene-rubber (SBR) blend by using melt blending method [32,33]. MWCNTs were completely localized into the PC phase, which cause the decrease in electrical resistivity as compared to pure PC or SAN, and during melt mixing; MWCNTs migrated from the SAN phase into the PC phase [32]. Hosseini et al. [33] studied the blending of PC with styrene-butadiene-rubber filled with MWCNTs prepared by solution casting technique. Su et al. [34] also investigated the formation of conductive network in PC/poly (vinylidene fluoride) (PVDF)/MWCNT NCs. They found that the electrical percolation threshold for PC/PVDF/MWCNT composites was much lower than those of MWCNTs-filled individual polymers i.e. PC or PVDF [34]. Xiong et al. [35] observed MWCNTs migration from PC to ABS phase when PC and ABS (high ABS content 70%) melt mixed with PC/MWCNT masterbatch. Monemian et al. [36] studied rheological, morphological and electrical properties of PC/ABS blends with varying amounts of MWCNTs. Maiti et al. [37] demonstrated a double percolation method in which PC melt blended with ABS/MWCNTs masterbatch to obtain electrically conducting NCs at the lower loading of MWCNTs with percolation threshold at 0.328 vol%. Maiti et al. [38] also reported preparation and characterization of conductive PC/styrene acrylonitrile (SAN) copolymer/MWCNTs NCs with lower MWCNTs content by melt blending of PC with SAN/MWCNT masterbatch. The electrical conductivity of 1.38×10^{-5} S/cm observed at MWCNTs content as low as ≈ 0.35 wt% [38]. In another study, Maiti et al. [39,40] reported that the electrical percolation threshold of the melt mixed PC/poly (ϵ -caprolactone) PCL/MWCNT NCs and PC/poly (butylene terephthalate) (PBT)/MWCNT NCs was observed at 0.14 wt% and 0.35 wt% loading of MWCNTs respectively. González et al. [41] reported the electrical conductivity of maleated styrene/ethylene-butylene/styrene (mSEBS) rubber modified PC/MWCNT NCs. The mSEBS lowered the percolation threshold (0.5 wt%) of NCs by means of a double percolation method [41]. In another study, maleic anhydride grafted styrene ethylene butylene styrene (SEBS-g-MAH) particles and CNTs were simultaneously introduced into a PC/poly (butylene terephthalate) (PBT) blend [42]. The incorporation of SEBS-g-MAH show enhancement in the impact response of the blend [42]. Taraghi et al. [43] studied the mechanical and electrical properties of PC/EPC/MWCNT NCs. The Young's modulus of PC/EPC (90/10) blends increased by 6.7% with highest impact properties upon addition of 1% MWCNTs. However the electrical percolation was observed at much lower MWCNT content i.e. in between 0.5% and 1% MWCNT to PC/EPC (10%) blend [43]. Although lot of work has been done on PC, PC/ABS or SAN or PCL or PBT or mSEBS or EPC etc. using different kind of conductivity filler. However no reports are available on the evaluation of MWCNTs effect on the properties of PC/EMA blends. Therefore here we are systematically evaluating the effect of MWCNTs on the properties of PC/EMA 95/5 blend.

In this work, PC/EMA-MWCNT NCs were prepared by the dilution of PC/MWCNT masterbatch by melt blending with PC/EMA blend (95/5 w/w) using the twin-screw extruder. Main aim of this study is to elucidate the effect of MWCNTs on the electrical and mechanical properties of PC/EMA blends. Morphological characterization by using scanning electron microscopy (SEM), transmission electron microscopy (TEM), Raman spectroscopy and X-ray diffraction (XRD) were done to investigate the degree of dispersion of MWCNTs in the PC/EMA blend. The influence of MWCNTs on EMI shielding properties of PC/EMA blend was also investigated.

2. Material and methods

2.1. Materials

Polycarbonate (PC) (LEXAN™ Resin 143 from SABIC Plastics with MFI = 10.5 at 300 °C with 1.2 kg load and density = 1.19 g/cm³) and ethylene methyl acrylate (EMA) copolymer (Elvaloy® AC 1330 from DuPont) having 70% by weight ethylene and 30% by weight methyl acrylate (MFI = 3 at 190 °C with 2.16 kg load and density of 0.95 g/cm³) are used in this investigation. Multiwalled carbon nanotubes (MWCNTs) NC 7000 grade with 90% carbon purity; length ~ 1.5 μm ; diameter ~ 9.6 nm and surface area 250–300 m² g⁻¹ obtained from Nanocyl S.A. Belgium were used as procured.

2.2. Preparation of PC/EMA-MWCNT NCs

For the preparation of NCs, we used PC/EMA blend and PC/MWCNT masterbatch.

(i) Preparation of PC/EMA blend

PC/EMA (95/5 w/w) blend was prepared by melt blending of PC with EMA using twin-screw extruder. The details of blend preparation and characterization have already been reported [25]. Required amounts of polymer granules were mixed with the help of high-speed mixer and then proceed by melt mixing using the twin-screw extruder. Prior to extrusion, PC and EMA granules were dried in oven for 12 h at 80 °C temperature. The temperature of the extruder used for melt compounding ranged from 140 to 270 °C and the screw speed was 150 rpm. The extruded strands were granulated and granules were dried in the vacuum oven before further processing.

(ii) Preparation of PC/MWCNT masterbatch

Masterbatch was prepared by melt blending of PC with 10 wt% of MWCNTs using twin-screw extruder. Prior to extrusion, PC and MWCNTs were dried in oven for 12 h at 80 °C temperature and mixed in high-speed mixer before melt blending. The temperature of extruder ranged from 238 to 280 °C and the screw speed is 200 rpm for melt compounding. The extruded strands were granulated and granules were dried in the vacuum oven before further processing.

(iii) Fabrication of PC/EMA-MWCNT NCs

PC/EMA-MWCNT NCs having the varying loading of MWCNTs were prepared by melt blending of PC/EMA (95/5) blend with PC/MWCNTs master batch using micro-compounder (Model: HAAKE Minilab II) at processing temperature 270 °C, screw speed 100 rpm and mixing time 5 min. Drying of PC/EMA blend and PC/MWCNT masterbatch before melt blending was performed at 80 °C for overnight in the oven to remove moisture. The details of formulation and sample designation for the PC/EMA-MWCNT NCs is given in Table 1. The schematic representation of the NCs fabrication is illustrated in Fig. 1.

2.3. Preparation of test specimens by injection moulding

The micro-injection molding machine (Thermo Scientific HAAKE Mini) was used for the preparation of test specimen of PC/EMA-MWCNT NCs for tensile and impact testing. Cylinder temperature, mold temperature and pressure for injection molding were 250 °C, 100 °C and 640 bar respectively.

Table 1
Details of formulations, sample designation and electrical conductivity of PC/EMA-MWCNT NCs.

Sample Designation ^a	Polycarbonate (wt%)	Ethylene methyl acrylate (wt%)	MWCNT loading (phr)	Electrical conductivity (S cm ⁻¹)
PCE5	95	5	–	1.23×10^{-16}
PCENT0.25	95	5	0.25	2.02×10^{-16}
PCENT0.5	95	5	0.5	2.88×10^{-16}
PCENT1	95	5	1	3.07×10^{-9}
PCENT2	95	5	2	3.18×10^{-6}
PCENT3	95	5	3	3.534×10^{-5}
PCENT4	95	5	4	2.72×10^{-4}
PCENT5	95	5	5	8.77×10^{-4}
PCENT10	95	5	10	1.56×10^{-3}

^a Where PC – Polycarbonate, E – Ethylene-methyl acrylate, NT – Multiwalled carbon nanotube, Numerical value – MWCNT content.

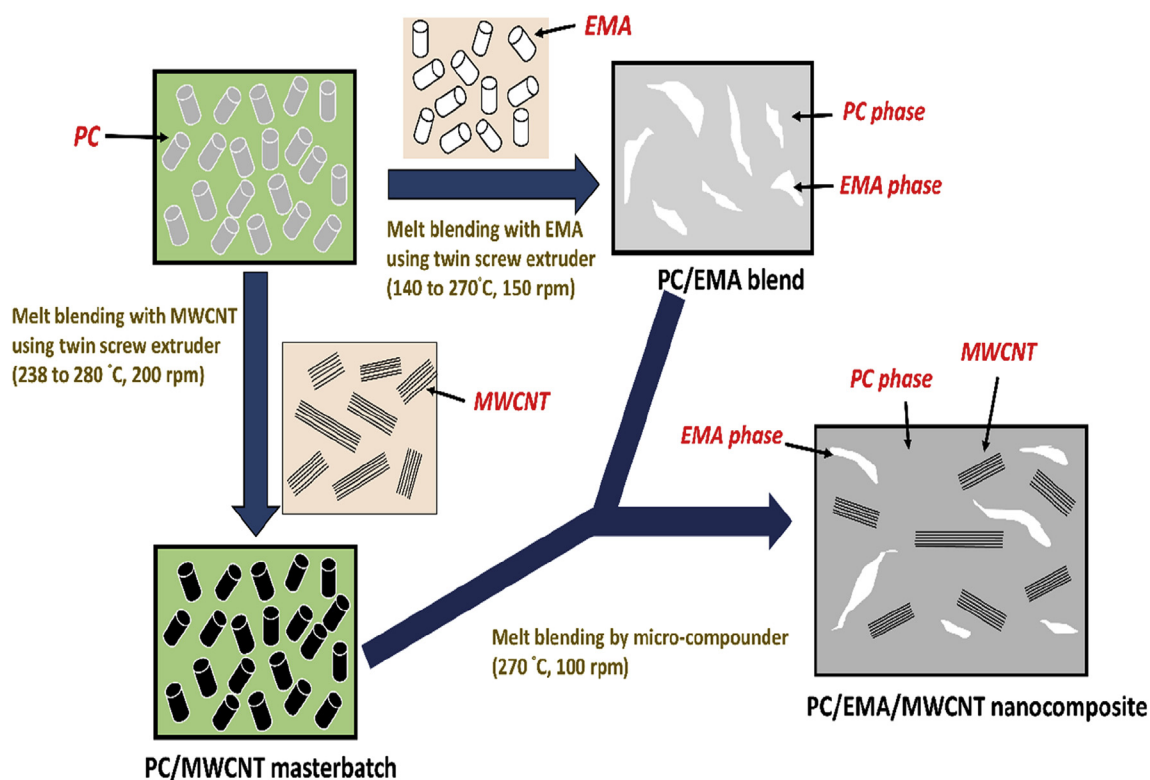


Fig. 1. Preparation of PC/EMA blends and PC/EMA-MWCNT NCs.

2.4. Characterizations of NCs

2.4.1. Surface morphology

The surface morphology of cryofractured PC/EMA-MWCNT NC samples were examined by using SEM Zeiss EVO 50 at the magnification of 30,000. The cryofractured surfaces of molded specimen were coated with gold. The degree of dispersion of MWCNTs in PC/EMA matrix was investigated by HRTEM (FEI Tecnai TF20). TEM images of the microtomed samples were taken at the voltage of 200 kV.

2.4.2. Structural characterization

XRD patterns of PC/EMA-MWCNT NCs were recorded on a PANalytical instrument (PW3050/60 Xpert) with Ni-filtered CuK_α radiation. Injection molded samples were used for this study and scanned from $2\theta = 5^\circ$ – 60° at a rate of $2^\circ/\text{min}$. Raman spectrum was used to evaluate the interaction of MWCNTs with PC/EMA blend. Raman spectra were recorded using diode laser at 785 nm excitation.

2.4.3. Mechanical properties

Tensile strength was measured using Zwick Z010 universal testing machine according to ASTM D-638. Notched impact strength was measured using molded specimen on impact tester (Tinius Olsen) according to ASTM D256. At least five samples were tested for each composition.

2.4.4. DC electrical conductivity

The direct current (DC) electrical conductivity of PC/EMA-MWCNT NCs was performed on the molded bars and determined by using Keithley semiconductor characterization system in two-probe configuration. Minimum five samples for each composition were tested.

2.4.5. Electromagnetic interference shielding effectiveness (EMI SE)

EMI SE of PC/EMA-MWCNT NCs was measured by recording the scattering pattern on Agilent E8362B Vector Network Analyzer (VNA) using two port measurement technique in X-band (8.2–12.4 GHz). The rectangular samples of 3 mm thickness were

placed inside the cavity of sample holder connected between the waveguide flanges of the network analyzer. Reflected and transmitted signals from the sample were measured by VNA.

3. Results and discussion

3.1. Morphological characterization of PC/EMA-MWCNT NCs

Fig. 2a–f show the SEM micrographs of cryofractured surfaces of PCE5 (95/5w/w) blend and PC/EMA-MWCNT NCs, having 0.5, 2, 4, 5 and 10 phr loading of MWCNTs. Both PC and EMA are generally immiscible in nature because of their large melt viscosity difference during melt mixing. PC having 5 wt% of EMA shows debonding of EMA particles with the voids which indicate adhesion between PC and EMA in Fig. 2a. As seen in Fig. 2b–f, small voids were presented which indicate the debonding and low interfacial adhesion. The distribution of MWCNTs in the matrix is clearly evident from small filament-like structures to be protruding out of the polymer matrix. A close examination of the morphology of NCs (Fig. 2b–f) shows the uniform dispersion of MWCNTs in the PC/EMA matrix.

The MWCNTs dispersion in PC/EMA matrix was analyzed by

using HRTEM. Fig. 3 shows the HRTEM images of PC/EMA-MWCNT NCs i.e. PCENT0.5, PCENT2, PCENT5 and PCENT10. As Fig. 3 shows, the MWCNTs are mainly located in the PC phase and the minor amount of the MWCNTs are seen either at the interface or in the EMA phase. Therefore, the nature of the dispersed phase (EMA) preserved its morphology in the NCs. So, this is good for PC toughening because there is no increase in stiffness. Thus, toughening property of PCE5 blend maintained in PC/EMA-MWCNT NCs. The localization of the MWCNTs in the PC matrix could be due to the interactions of the MWCNTs with the carbonate groups of PC. Analysis of the TEM micrographs of NCs exposes that the MWCNTs are mostly untangled and randomly dispersed mainly in PC phase. No additional agglomeration of the MWCNTs is seen in the NCs having higher amounts of MWCNTs.

3.2. Structural characterization of NCs

The XRD patterns of PCE5 and PC/EMA-MWCNT NCs are displayed in Fig. 4. For PCE5, the X-ray diffraction pattern shows a broad main characteristic peak at $2\theta = 17.2^\circ$ and the position of the characteristic peak remain unchanged after incorporation of

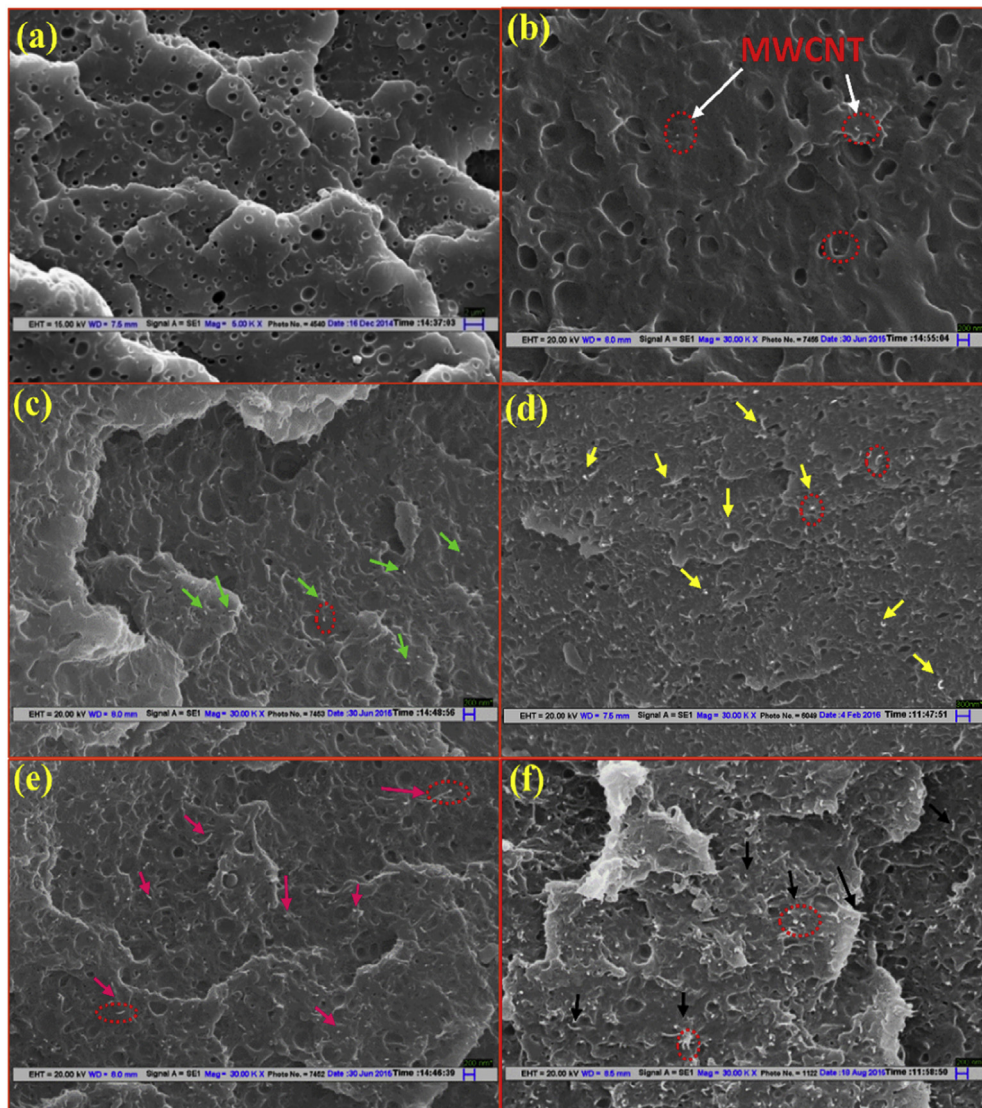


Fig. 2. SEM micrographs of the surface morphology of: (a) PC, (b) PCE5, (c) PCENT0.5, (d) PCENT2, (e) PCENT4, (f) PCENT5, and (f) PCENT10 NCs.

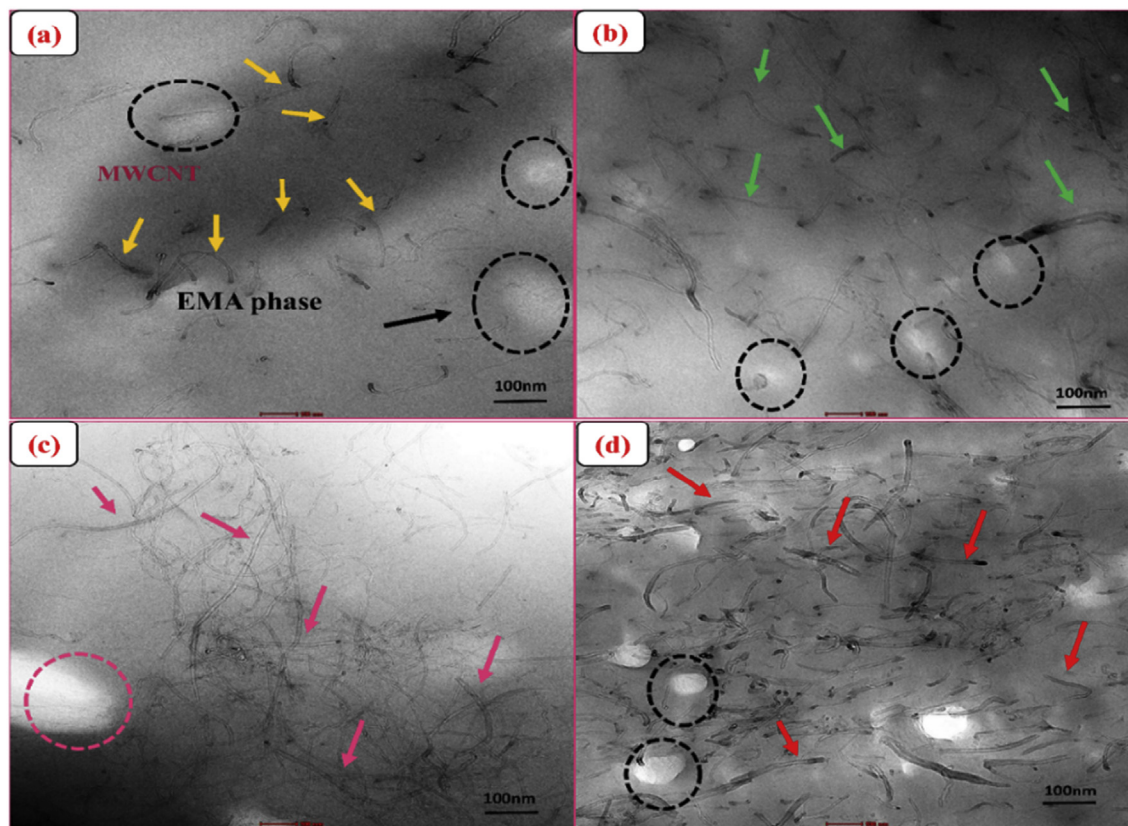


Fig. 3. HRTEM micrographs of: (a) PCENT0.5, (b) PCENT2, (c) PCENT5, and (d) PCENT10.

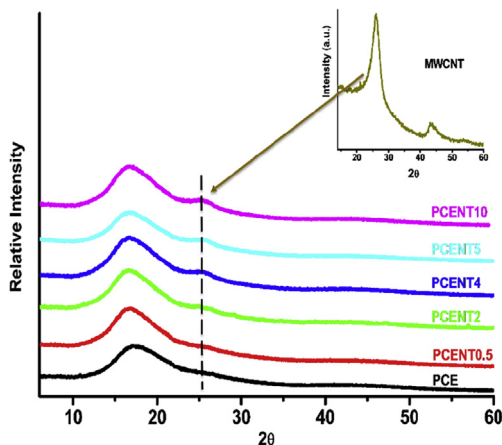


Fig. 4. X-ray diffraction pattern of PCE5 and PC/EMA-MWCNT NCs.

MWCNT. Incorporation of MWCNT brings about a new peak at $2\theta = 25.4^\circ$ that shows (002) planes of carbon nanotubes along with the interlayer spacing between the graphitic layers of MWCNT. There is no change in the crystal structure of PCE5.

Raman spectroscopy was carried out to study the interaction between PCE matrix and MWCNTs in the NCs. Raman spectra of MWCNT, PCE5 and PC/EMA-MWCNT NCs are displayed in Fig. 5a–d. The Raman spectrum of MWCNTs show two characteristic bands i.e. the D and G band which located at 1348 cm^{-1} and 1571 cm^{-1} respectively. Raman band in the spectrum of MWCNTs, named 2D, is located at 2690 cm^{-1} .

It can be seen from Fig. 5c that the Raman bands of PCE5

broadened and almost disappeared with increasing concentration of MWCNTs in NCs. This may be due to the interaction of PCE5 with MWCNTs. In case of PCE5, a peak was observed at 1605.8 cm^{-1} whereas in MWCNT peak due to 'G' band was observed at 1571 cm^{-1} . In PC/EMA-MWCNT NCs, a doublet was observed. The peak at 1605.8 cm^{-1} (due to matrix) and G band (1571 cm^{-1} due to MWCNT) shifted to higher wavenumber (Fig. 5c and d). Thus shift in peak positions confirms the interaction between matrix and filler. This has also been reported by different researcher in different matrix and filler system [44–46].

3.3. Mechanical properties of NCs

The mechanical properties of the NCs are affected by the degree of dispersion of nanofiller (MWCNTs) in the matrix and interfacial interaction with the matrix. If there is the agglomeration of nanofiller (poor dispersion) in the matrix which generally occurs at higher loading of filler, it may lead to decrease in the mechanical properties. So uniform dispersion of MWCNTs in PC/EMA-MWCNT NCs is required for superior mechanical properties.

The variation in tensile strength, elongation at break and tensile modulus of the PCE5 and PC/EMA-MWCNT NCs with the varying loading of MWCNTs (0.25–10 phr) are shown in Fig. 6a–c. There is a remarkable enhancement of tensile strength and tensile modulus of NCs with increased loading incorporation of MWCNTs in PCE5 blend. Maximum tensile strength for PCENT5 and PCENT10 NCs reached up to 37 and 39% increase as compared to PCE5 blend (60.6 MPa) as shown in Fig. 6a. The tensile modulus of NCs also showed an increase with the increase in MWCNT content (Fig. 6b). Highest tensile modulus observed at 10 phr loading of MWCNT NCs (PCENT10) was 60% higher as compared to PCE5 blend. This might

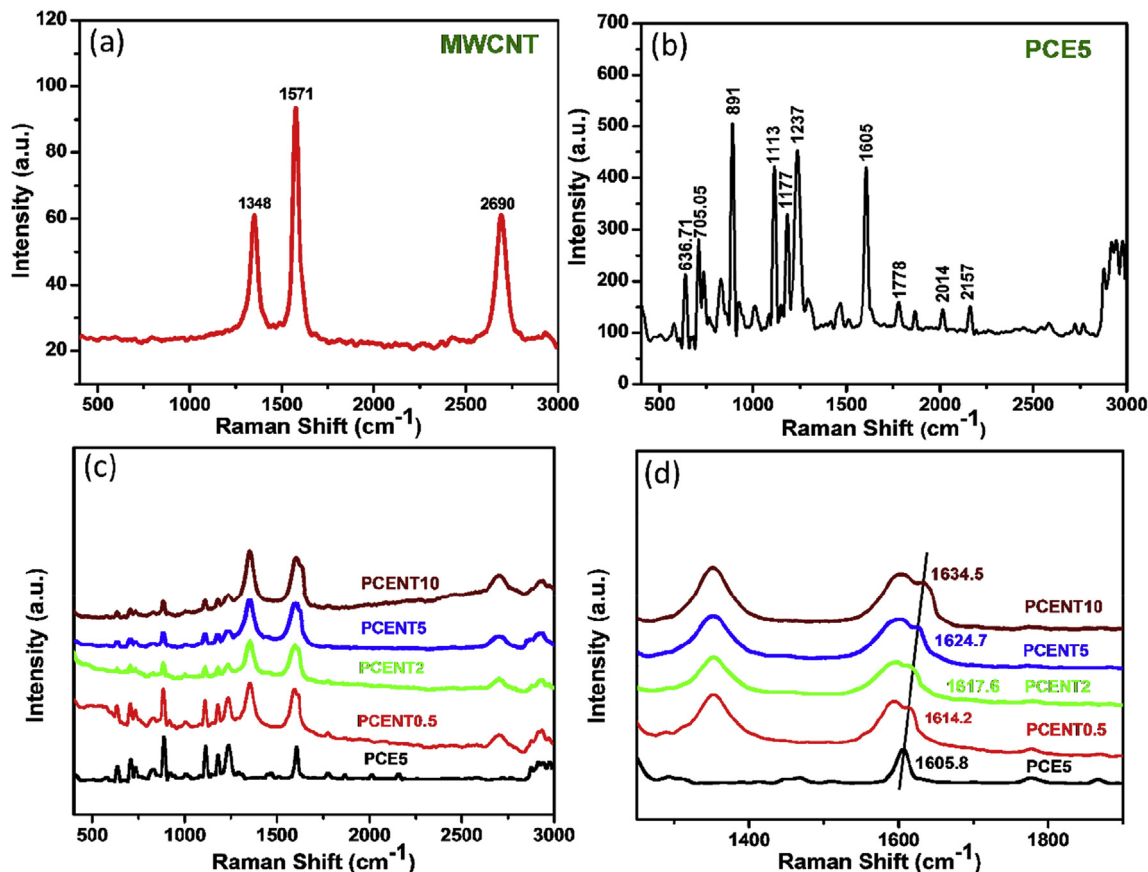


Fig. 5. Raman spectra of: (a) MWCNT, (b) PCE5, (c) PC/EMA-MWCNT NCs with different MWCNT loading, (d) Zoomed plot to show shifting in characteristic peak.

be due to stress transfer from polymer matrix to the MWCNTs. Taraghi et al. [43] reported maximum increment in the Young's modulus of the PC/EPC blend for about 6.7% by addition of 1 wt% of MWCNTs. González et al. [41] also reported for about 5% increment in the Young's modulus by addition of 0.5 wt% of MWCNTs in the PC matrix. Interfacial interaction between PCE5 blend and MWCNTs; and the dispersion of MWCNTs in the PCE matrix may cause an effective stress transfer between PCE and MWCNTs. As expected, elongation at break (Fig. 6c) decreased with the incorporation of MWCNTs. However, no definite trend was observed with increasing concentration of MWCNTs.

Fig. 6d shows the Izod notched impact strength of PCE5 blend and PC/EMA-MWCNT NCs (0.25–10 phr). PC has very low notched impact strength (~66 J/m). The notched impact strength of PCE blend (~318 J/m) showed 381% increment with the incorporation of very less amount of EMA (5%) as reported in our previous work [25]. In Fig. 6d, it can be seen that the impact strength of the NCs increases with the increase loading of MWCNTs upto 3 phr as compared to PCE5 blend. As MWCNTs loading increases (0.25–3 phr), the notched impact strength of PC/EMA-MWCNT NCs increases and then decrease with further increase in MWCNTs content (4–10 phr). Interesting result observed from this study is that the substantial increase in impact strength about 19% (378.03 J/m) was observed at only 1 phr loading of MWCNTs as compared to PCE5 blend. At the higher loading of MWCNTs (10 phr), impact strength of NCs was decreased which may be due to the adverse effect of MWCNTs agglomeration on the toughening. Taraghi et al. [43] reported that the impact strength of PC/EPC decreased by nearly 265% with addition of 0.5 wt % MWCNT and the highest impact properties has been observed in 1.0 wt % MWCNT.

3.4. Electrical conductivity of PC/EMA-MWCNT NCs

Electrical conductivity (EC) of PCE5 blend and PC/EMA-MWCNT NCs having varying amounts of MWCNTs is shown in Fig. 7. A significant increment in EC was observed with the increase in MWCNTs loading. Initially, at low loading 0.5 phr of MWCNT, the PC/EMA-MWCNT NCs showed conductivity value ($2.88 \times 10^{-16} \text{ S cm}^{-1}$) similar to the PCE ($\sim 10^{-16} \text{ S cm}^{-1}$). The EC of NCs displays a sharp rise (~seven orders of magnitude) at 1 phr of MWCNTs ($3.07 \times 10^{-9} \text{ S cm}^{-1}$), which indicate the formation of 3D electrically conducting network for electrical conduction. Thus these NCs showed electrical percolation in between 0.5 and 1 phr loading of MWCNTs. Abbasi et al. also reported percolation threshold in the PC/MWCNT NCs in between 2 and 3 wt% loading of MWCNTs [47]. Yamaguchi et al. observed percolation threshold in PC/MWCNT NCs at ~3.0 wt% MWCNTs loading [48]. In PC/EMA-MWCNT NCs, EC gradually increases with increasing content of MWCNTs beyond 1 phr loading. The highest EC observed for the PC/EMA-MWCNT NCs is about $1.56 \times 10^{-3} \text{ S cm}^{-1}$. The conductivity results of PC/EMA-MWCNT NCs are stated in Table 1. The electrical percolation threshold has been predicted by plotting the EC as a function of the MWCNT loading and performing data fitting using the scaling law [38,40,49,50].

$$\sigma = \sigma_0 (\rho - \rho_0)^t \quad (1)$$

where σ , σ_0 , ρ , ρ_0 and t represents the EC of the NCs, the constant related to the intrinsic conductivity of the filler is the volume fraction of filler, the volume fraction at the percolation threshold and the critical exponent related to the system

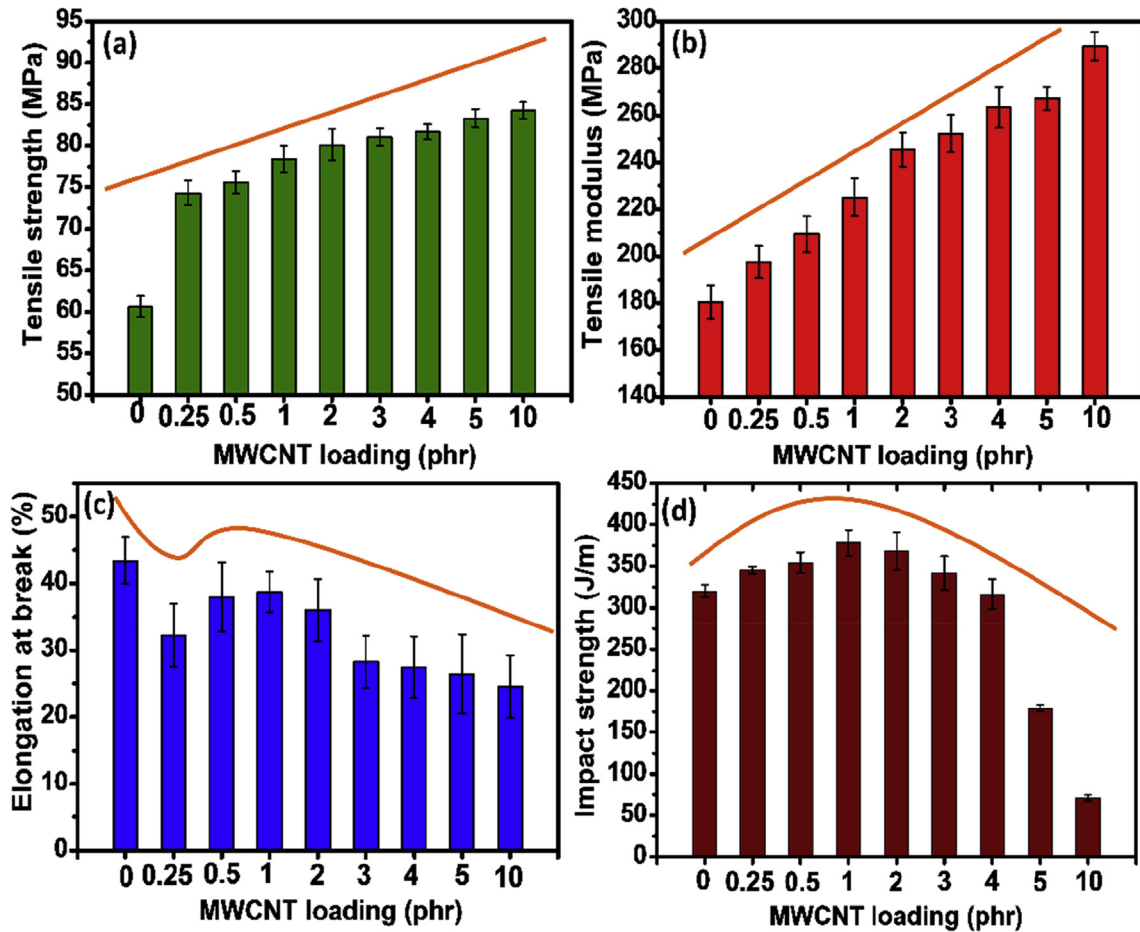


Fig. 6. Plot of (a) tensile strength, (b) tensile modulus, (c) elongation at break, and (d) impact strength of PC/EMA-MWCNT NCs with MWCNT loading.

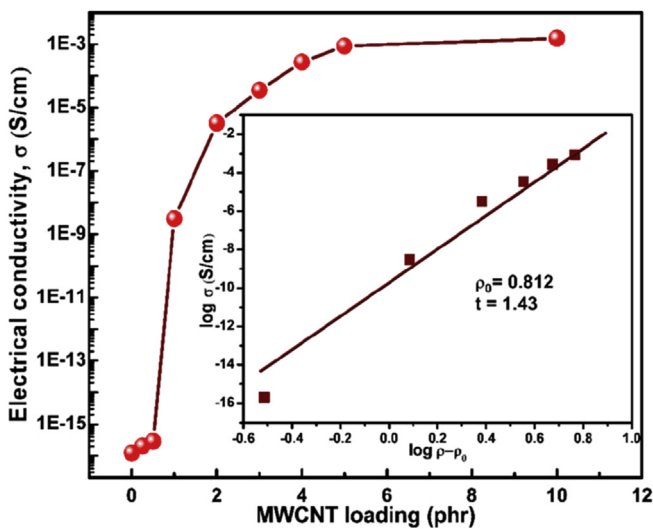


Fig. 7. Plot of electrical conductivity (σ) of PC/EMA-MWCNT NCs with MWCNT loading (phr). The inset shows the $\log(\sigma)$ vs. $\log(\rho - \rho_0)$ plot.

dimensionality respectively [51]. This equation can also be written in logarithm form:

$$\log(\sigma) = \log(\sigma_0) + t \log(\rho - \rho_0) \quad (2)$$

The percolation threshold is the minimum filler content where the first continuous network of filler is formed within the matrix. Higher critical exponent and low percolation threshold value are indicative of a uniform dispersion of filler within the matrix. The linear regression data fitting (inset Fig. 7) gives $\rho_0 = 0.812$ phr and $t = 1.43$ for PC/EMA-MWCNT NCs. The theoretical values of the critical exponent (t) varies from 1.6 to 2 for a three-dimensional percolating system but the experimental values for different polymer/CNT NCs ranged from 1.4 to 5.5 [52]. The critical exponent value obtained from the fit is in good agreement with experimental predictions.

3.5. Electromagnetic interference shielding (EMI SE)

The EMI SE is the ability of a material to attenuate incident electromagnetic wave. The EMI shielding is a direct result of the absorption of the wave as it passes through the shield's thickness, the reflection of the wave from the front face of the shield and multiple reflections of the waves at various interfaces. The presence of charge carriers in material helps in electromagnetic wave reflection via reflection mechanism electromagnetic wave penetrate through the material and get attenuated via the absorption. Absorption loss is more important for the magnetic field of electromagnetic wave than the electric field. Therefore the electric field of electromagnetic wave is mostly reflected at the interface. The total SE of a material can be expressed in logarithmic power ratio as [53].

$$SE (dB) = (SE_R + SE_A + SE_M) = 10 \log_{10} \left(\frac{P_t}{P_i} \right) \quad (3)$$

Where SE_A , SE_R and SE_M are the shielding effectiveness due to absorption, reflection and multiple reflections respectively and P_i and P_t are the power of incident and transmitted EM waves respectively. As the P_t is always less than P_i , therefore, SE is a negative quantity. So, a shift toward more negative value means the increase in the magnitude of SE. The multiple reflection term (SE_M) can be ignored, if the contribution of absorption to EMI SE is more than -10 dB, thus SE can be written as

$$SE (dB) = SE_R + SE_A \quad (4)$$

Several studies have been reported on EMI shielding properties of PC/CNT NCs [49,54–60]. These studies show EMI SE of NCs increases with increase in MWCNT content or electrical conductivity and in most of these studies EMI shielding is dominated by absorption. EMI SE of PC/EMA-MWCNT NCs with different loading of MWCNTs was analyzed in X-band (8.2–12.4 GHz) (Fig. 8a). The results showed that the average SE_T value increases with increase in the MWCNT loading e.g. PCENT0.5 gives a poor EMI shielding response ($SE \sim -3$ dB) whereas the SE about -26 dB obtained for PCENT10 which relates to a blocking of more than 99% of the incident EM radiations. Pande et al. [55] also reported only -21 dB SE for acid functionalized MWCNT/PC NCs with 10 wt% MWCNT

loading. Further, SE_A and SE_R were investigated and it was found that both SE_R and SE_A increases with the increase of MWCNT loading as shown in Fig. 8b and c, respectively. Fig. 8d shows that, though both SE_A and SE_R increase with MWCNT loading, SE_A increases more rapidly as comparison to the corresponding SE_R . This behavior can be attributed to the EMI shielding mechanism being dominated by absorption.

The increment in EMI shielding of NCs with the increase in MWCNT content can be due to the formation of conductive 3D network of MWCNTs within insulating PCE5 blend and availability of the larger number of charges to interact with the incident electromagnetic waves. The obtained maximum EMI shielding (-26 dB) crossed the limit required for commercial applications (-20 dB), which proposes that these PC/EMA-MWCNT NCs are promising EMI shielding material with improved mechanical properties. Several authors have reported the EMI shielding properties of PC NCs based on different nanofiller as shown in Table 2.

4. Conclusions

The main objective of this study was to investigate the effect of MWCNT on electrical and mechanical properties of PCE5 blend. Mechanically strong and electrically conductive PC/EMA-MWCNT NCs were prepared by melt recirculation using twin screw extruder. The micro-structural studies (SEM and TEM images)

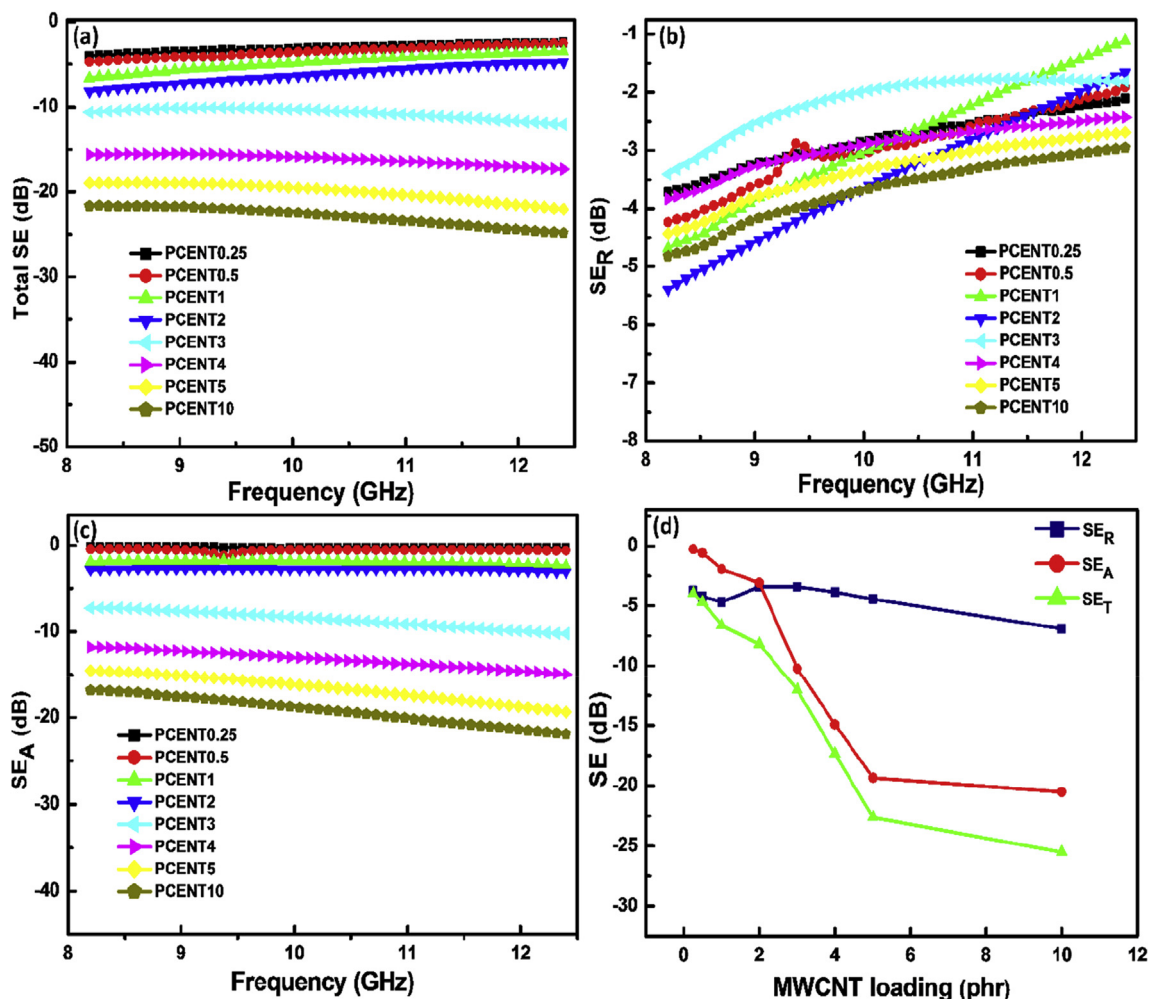


Fig. 8. Variation in EMI SE of PC/EMA-MWCNT NCs: (a) Total SE, (b) SE_A , (c) SE_R in X-band (8.2–12.4 GHz), and (d) total SE with MWCNT loading.

Table 2

A comparative study of EMI SE of PC and PC blends with different conducting fillers.

Polymer matrix	Conducting filler	Loading	Frequency (GHz)	SE _T (dB)	Ref.
PC/ABS	MWCNTs	1.5 wt%	5–12	–1.98	[54]
PC	Acid functionalized MWCNTs	10 wt%	8.2–12.4	–21	[55]
PC/ABS	Ni-coated carbon fiber	30 phr	1	–47	[56]
PC/ABS	Carbon fiber	30 phr	1	–33	[56]
PC	MWCNTs	7 wt%	1.2	–16	[57]
PC/ABS	Ni-coated carbon fiber treated with Coupling agent	10 phr	0.02–1	–23	[58]
PC/ABS	MWCNT	3 phr	0.05–1.5	7	[59]
PC	Carbon black	5 wt%	8.2–12.4	–10.78	[60]
PC	Graphite	30 wt%	8.2–12.4	–5.44	[60]
PC/EMA	MWCNTs	10 phr	8.2–12.4	–26	Our work

revealed that the MWCNTs are uniformly dispersed in PCE5 blend. The spectroscopic (XRD and Raman) study has confirmed the better interaction between the PC/EMA and MWCNT. The tensile strength and modulus of PC/EMA-MWCNT NCs increased about 39 and 60% respectively, upon incorporation of 10 phr of MWCNTs. The impact strength of NCs improved by 19% up to 1 phr MWCNT loading. The electrical percolation threshold of the PC/EMA-MWCNTs occurred at low loading i.e. between 0.5 and 1 phr loading of MWCNTs. Additionally, highest electrical conductivity about $1.56 \times 10^{-3} \text{ S cm}^{-1}$ was achieved for NCs having 10 phr of MWCNTs and highest EMI SE for PC/EMA-MWCNT NCs was found to be –26 dB in X-band (8–12 GHz) which is mainly used for VSAT systems and satellite communication applications. From these studies, it can be concluded that the mechanically strong, electrically conducting lightweight polymer shield can be prepared using PCE5 blend as matrix and MWCNT (10 phr) as filler.

Acknowledgment

Sincere thanks to University Grants Commission (UGC), India for supporting with financial help to one of the authors [Nisha Bagotia].

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