Research Article

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Development of vegetable oil-based conducting rigid PU foam

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Abstract: In this study, carbon fibre powder has been used as reinforcement to enhance the electrical conductivity of bio-based rigid polyurethane foam. Effect of carbon fibre incorporation on the mechanical, thermal and flame retardant properties has also been investigated. Results concluded that the foams with 8% carbon fibre concentration showed up to 288% increase in compressive strength. Furthermore, up to 28% decrease in the peak of heat release rate (PHRR) was observed on the incorporation of carbon fibre powder. Additionally, the rate of smoke production was also found decreased for carbon fibre reinforced foams. Foams with 8% and 10% carbon fibre concentration show conductivity of 1.9×10^{-4} and 7.1×10^{-4} S/m, respectively. So, carbon fibre powder may be used as a potential filler to enhance the electrical conductivity of rigid foams without compromising the other properties.

Keywords: four probe measurement; heat release rate; mechanical strength; thermal conductivity; weight loss

1 Introduction

Electromagnetic interference (EMI) is the disturbance generated by some undesirable radiated signals emitted by electronic instruments which may affect the performance of other electronic devices. Nowadays, an expeditious rise in the use of wireless devices for communication, such as laptops, smartphones, routers, and others are polluting their surroundings in terms of electromagnetic pollution, which may be dangerous for the health of human beings as well as for information security. Therefore, an appropriate

EMI shield is required to protect the environment from electromagnetic waves used by many vital applications such as air traffic control, weather radar, satellite communications and others (1,2). These materials may also be used for evading radar detection by absorbing electromagnetic radiations. Metallic coating has been extensively used as EMI shielding materials, but they always suffer from some shortcomings of high density, poor resistance to corrosion and high cost of processing. As alternatives, polymeric foams incorporated with conductive fillers are explored to fabricate lightweight and tough shielding materials. These polymeric foams are a suitable material for such applications due to their various attractive properties such as better mechanical and electrical properties with lower density. A wide range of polymers, such as epoxies (3), poly (methyl methacrylate) (PMMA) (4,5), polyurethane (PU) (6), polystyrene (PS) (7) and polypropylene (PP) (8) have been utilized to develop EMI shielding foams. Kuang et al. (9) prepared poly lactic acid – MWCNT nanocomposite foam for EMI shielding applications and observed that conductivity of 3.4 S/m was obtained using the foam with 10 wt% of MWCNT and density 0.3 g/cm. Li et al. (10) fabricated epoxy-MWCNT nanocomposite foam and obtained a conductivity of 3.04×10^{-2} S/m by the addition of 5 wt% of MWCNT. Yan et al. (2) prepared polystyrene nanocomposite using reduced graphene oxide(rGO) and achieved electrical conductivity up to 43.5 S/m with 3.47 vol% loading of rGO. Hwang et al. (11) prepared polybutylene terephthalate (PBT)/carbon fibre composite and investigated the effect of carbon fibre on the EMI shielding performance. It was concluded that carbon fibre loading should be greater than 30 wt% to get better EMI shielding effectiveness. Zhang et al. (12) fabricated PMMA based foam with density 0.22-0.38 g/cm³ incorporated with Fe₃O₄ and MWCNT. It was observed that foams with 1.63% hybrid filler loading showed an electrical conductivity of 2×10^{-4} S/m. Li et al. (13) fabricated ultrathin carbon foams by the pyrolysis of polyimide/graphene composite foams. It was observed that up to 24 dB electromagnetic interference (EMI) shielding effectiveness exhibited by these graphene based foams with conductivity up to 2300 S/cm.

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Besides these materials, PU foam may be used as a promising material due to its low density and good mechanical properties. Commercially, PU foams are available in different forms such as flexible, rigid or elastomeric depending upon their structure. Rigid polyurethane foams (RPUFs) have been used in a wide variety of applications such as building and construction industry, transportation and others, for the insulation purpose. RPUF has also been used in radomes and high-speed aircrafts due to its ability to allow electric and magnetic waves to pass through it. Owing to its high dielectric constant and low weight it is being used in different fields of electronic industry such as potting and encapsulation of electronic components, microwave absorbers, and others. RPUF may also be used for electromagnetic wave absorption by incorporating some functional filler. Functional fillers contribute the plastic materials with a much wider range of properties including some unique properties not normally associated with plastics, such as high electrical conductivity or low flame retardancy. Li et al. (14) studied the effect of sandwich and gradient configuration on the EMI shielding performance and concluded that multilayered polyurethane graphene composite may be used as a high-performance composite for microwave absorption and EMI shielding. Farhan et al. (15) prepared a different type of carbon foams using powdered PU and carbon precursors novolac and pitch. Silicon carbide (SiC) nanowires were grown to enhance the absorption properties of this carbon foam. A maximum EMI shielding of 79.50 dB cm³/g was achieved in the carbon foam containing 20% Si content with very low conductivity. Esfahani et al. (16) incorporated surface functionalized graphene sheets in thermoplastic PU and their EMI shielding effect has been investigated. Results showed that higher electrical conductivity and improved dielectric properties were achieved due to the stronger interfacial interaction between the filler and the TPU matrix. The TPU film with 5 vol% graphene and thickness of 1 mm exhibited commercially relevant EMI shielding effectiveness of 25 dB in the X-band frequency range. Commercially, PU has been prepared by the reaction of polyols with the polyisocyanate, both of them are petroleum-based raw materials. But, due to the depletion in petroleum resources and rising concern about the environment, bio-based raw materials are the requirement of the modern world (17-20). Ibrahim et al. (21) fabricated castor oil based PU films to be employed as a base material for electrolytes. It was observed that the conductivity of PU films increased from 1.18×10^{-9} S/m to 1.42×10^{-4} S/m on the incorporation of 30 wt% of LiI salt. Nevertheless, the

application of bio-based conductive RPUF has not been explored so far. So, in this study, we are exploring the electrical conductivity of bio-based RPUF incorporated with carbon fibre in varied proportion. The mechanical, thermal and flame retardant properties of these foams have also been investigated.

2 Materials and methods

2.1 Materials

Castor oil (99.9%, Hydroxyl value = 160 mg equivalent KOH/g) is purchased from Thomas Baker Chemicals (Pvt) Ltd and diphenylmethane diisocyanate (PMDI, 30-32 NCO %) is obtained from Krishna Enterprises. n-Pentane (99.5%) and Silicon oil, are purchased from CDH. Catalyst DABCO 33 LV is purchased from Sigma-Aldrich. Glycerol (99%) is supplied by Sisco Industries Pvt. Ltd. Carbon fibre is purchased from CFW Enterprises with tensile strength ≥ 3500 GPa, density 1.65-1.75 g/cm³. Carbon content $\geq 98\%$, electrical resistivity 1.5×10^{-33} Ω /cm and mesh size 50-1000. All the reagents were of analytical grade and used as supplied.

2.2 Methods

The RPUFs are obtained by the same method as reported in the literature (22-24). In brief, the procedure is as follows:

The modification of castor oil is carried out under the inert atmosphere of nitrogen using 2:1 ratio of castor oil to glycerol at the temperature 180-200°C for 4 h. The predetermined quantity of the carbon fibre powder is added to the modified polyol (Hydroxyl value = 350-450 mg equivalent KOH/g) taken in a beaker. Prior to addition, the fillers have been dehydrated in a vacuum oven at 60°C for 4 h. Then calculated amount of other ingredients such as catalyst, surfactant and blowing agent is added to the contents of the beaker and thoroughly mixed to form polyol-premix. A calculated amount of MDI is then added to the beaker. The resulted reaction mixture is poured into a metal mould (100 mm $\times$ 100 mm $\times$ 10 mm) coated with releasing agent i.e. silicone oil and a free rise foam is prepared.

To ensure complete curing, the moulds are left to stand for 72 h. After demoulding, the resulted RPUF is cut into desired dimensions and tested for its mechanical, thermal and anti-flammable properties. Figure 1 shows the reaction scheme for polyurethane foam synthesis and modification of castor oil. Table 1 presents the foaming

formulation of castor oil based RPUFs modified with different concentration of carbon fibre powder.

3 Characterization

Mechanical, thermal and morphological analysis of castor oil based RPUFs incorporated with different concentration of carbon fibre is performed to find out the performance

Table 1: Foaming formulation of castor oil-based RPUF.

Material	Amount (pbw)
Modified Polyol	100
DABCO 33 LV	3
n-Pentane (blowing agent)	10-15
Silicone oil (surfactant)	3
Carbon fibre	2-10
MDI	110

Pbw = parts by weight of Polyol

shown by these foams. Various characterization techniques used are described below.

3.1 FTIR and ^1H NMR analysis

The chemical structure of transesterified castor oil was determined using FTIR spectroscopy on Nicolet 380 by preparing KBr pallets. The spectra were observed in the $450\text{--}4000\text{ cm}^{-1}$ range. ^1H NMR of modified and virgin castor oil was also conducted (Bruker Avance II-400) at SAIF, Punjab University, Chandigarh, using dimethyl sulphoxide (DMSO) as a solvent. Characterization of prepared RPUFs was conducted using perkinElmer spectrophotometer version 10.5.3.

3.2 Mechanical testing

The mechanical properties of the castor oil based RPUF samples have been determined according to the standard procedures. Testing is conducted on three specimens

Reaction scheme of transesterification reaction

Reaction scheme of Polyurethane formation

Figure 1: Reaction scheme of transesterification and polyurethane formation.

of each concentration and the average value has been reported. Compressive and flexural properties of the resulted foams are measured at room temperature using Instron (model No. 3369) universal testing machine (UTM). The compression tests are performed according to the ASTM D-695. Specimens of dimensions 25 mm × 25 mm × 25 mm are cut from the foam in the in-plane direction and tested for 10% compression. The compression strength has been measured along parallel foam rise direction. The flexural tests are performed according to the ASTM D-790. Specimens of dimensions 80 mm × 10 mm × 4 mm are cut from foam perpendicular to foam rise direction and loaded under three-point bending. The rate of crosshead movement is fixed at 2 mm/min for each sample.

3.3 Thermogravimetric analysis (TGA)

Thermogravimetric analysis (TGA) was performed utilizing a thermogravimetric analyzer (Perkin Elmer 4000) in a nitrogen atmosphere with a heating rate of 10°C/min. and the temperature ranging from 50 to 700°C.

3.4 Cone calorimeter testing

The fire performance of RPUF samples was analyzed with a Cone Calorimeter (Jupiter Electronics, Mumbai) according to ISO 5660-1 standard at an incident heat flux of 35 kW/m². The size of the samples was kept 100 mm × 100 mm × 20 mm. This instrument is capable of recording the time to ignition (TTI), total heat release (THR), heat release rate (HRR), smoke production rate (SPR) and total smoke production (TSP) etc.

3.5 Conductivity measurement

The conductivity of prepared rigid foam samples was measured by using four probe set-up (SES Instruments Pvt. Ltd., Roorkee).

4 Results and discussion

Carbon fibre in different proportion is added to PU foam to provide some desired functional properties. The foam architecture depends on the particle size and the dispersion of the filler in the reacting mixture. Moreover, an interaction between the filler and polymer matrix is the important parameter governing the mechanical properties of reinforced PU foam (25).

4.1 FTIR and ¹H NMR analysis

Figure 2 shows the ¹H NMR spectrum of modified and virgin castor oil. The sharp singlet at 1.23 ppm is attributed to the proton associated with hydroxyl group. The signal obtained as a multiplet at 1.50 ppm is attributed to the methylene protons of aliphatic chain. NMR spectrum of modified castor oil shows signals at 2.26 ppm and 3.29 ppm, which is assigned to the presence of proton α to carbonyl carbon of the ester bond. The multiplet signal at 4.25 ppm corresponds to the proton α to oxygen atom. The signal obtained at 5.20 ppm is associated with proton attached to alkene carbon. A signal at 0.87 ppm is assigned to terminal methyl proton. Similar results were obtained by Narwal et al. (26) Modified castor oil shows similar peaks except increase in intensity of peak at 1.23 ppm due to hydroxyl proton, which confirms the increase in hydroxyl value of castor oil by transesterification reaction. In addition, peaks get broadened in the NMR spectrum of modified castor oil, which is attributed to the broad range of different molecular weight compounds in modified polyol.

The FTIR spectra of polyol samples confirmed the presence of the C–H symmetric and asymmetric stretching vibrations of CH₂ groups at 2925.3 cm⁻¹ and 2854.2 cm⁻¹ respectively. The intense band at 1742.9 cm⁻¹ was due to C=O stretching of ester groups and the absorption bands at 1480.3 and 1373.8 cm⁻¹ were attributed to CH₂ bending and C–H bending vibration, respectively. As illustrated in Figure 3a, the broad and strong band corresponding to the OH group (3357.3 cm⁻¹) in the castor oil was also noted and intensity of this peak increases in the spectra of polyol, which confirms the increase in hydroxyl number by the transesterification reaction (26).

The FTIR spectrum of RPUFs shows all the characteristic peaks of urethane linkage, as seen in Figure 3b. Absorption maxima at 3331-3411 cm⁻¹ is attributed to stretching vibrations of N–H groups present in urethane linkages, while peaks at 1510-1523 cm⁻¹ attributed to the bending vibrations of these groups. Incorporation of carbon fibre shifted the band towards the lower wavenumber. Signals associated with the stretching vibrations of C=O bonds were shown at 1705-1738 cm⁻¹. Absorption bands characteristic to stretching vibrations of C–N bonds present in urethane linkages were also observed at 1206-1261 cm⁻¹.

The absorption maxima at 2854-2870 and 2925-2963 cm⁻¹ are attributed to the symmetric and asymmetric stretching vibrations of C–H bonds present in aliphatic chains (21,27). Intensity of bands associated with stretching vibration of C=O groups and C–H bonds at 1705-1738 cm⁻¹ and 2854-2963 cm⁻¹, respectively

Figure 2: ^1H NMR of (a) modified polyol and (b) castor oil.

Figure 3: (a) FTIR of castor oil and modified polyol, (b) FTIR spectra of prepared RPUFs.

decreases in the foams incorporated with carbon fibre. It is attributed with the heterogeneity produced by the carbon fibre consequently decreasing the mechanical strength. Additionally, the absorption band around

2250 cm^{-1} , which is associated with $-\text{NCO}$ groups, was not observed up to 8% concentration of filler. It indicates the reaction of all NCO groups with the hydroxyl groups of polyol to synthesize RPUF. While RPUF with 10% concentration of carbon fibre shows a small peak at 2277 cm^{-1} and broadening of bands of stretching vibrations of N-H groups, which indicates the incomplete reaction between polyol and isocyanate as well as deterioration in the structure of RPUF.

4.2 Mechanical properties

Mechanical properties of PU foam are influenced by several factors such as density of the foam, cell geometry as well as number and size of cells. In general, foams with higher density are expected to be more rigid which in turn exhibit higher mechanical strength. PU foam without fillers has a large number of cells with a comparatively larger cell size, but when carbon fibre is incorporated, it is evident from SEM images that foam cell size decreased.

Figure 4 shows the change in mechanical properties of rigid polyurethane foam on the addition of carbon fibre powder. Foam with 8% concentration of carbon fibre shows higher mechanical properties with compressive strength 6.88 MPa and flexural strength 2.97 MPa, which is almost 3 times in comparison to the unreinforced foams (Figure 4a). Figure 4c shows the variation in specific strength or reduced strength (strength/density) on increasing the concentration of carbon fibre powder. It is observed that the specific strength decreases initially but again on increasing the concentration of filler up to 8%, there is an increase in the specific compressive

Figure 4: Plots of (a) mechanical strength vs. filler concentration, (b) density vs. filler concentration, (c) specific strength vs. filler concentration.

strength and specific flexural strength by 28% and 24% respectively as compared to the neat foam. This behaviour is attributed to the decrease in cell size and increase in cell number as more cell walls and struts per unit area of PU foams are present to support the foam structure under loading. This is also confirmed by SEM images of RPUFs as shown in Figure 5.

An initial slight decrease in the specific strength is attributed to the heterogeneity produced by the addition of filler, it is also confirmed by the FTIR of carbon fibre incorporated RPUFs. Furthermore, incorporation of fillers in the cell walls and struts strengthened the foam structure, consequently increasing the mechanical strength. It is evident from the literature that hydrogen bond formation

among urethane groups greatly contributes to the strength of RPUFs. But the filler introduced may interfere with the hydrogen bond formation, thus causing a negative effect on the properties of RPUFs. The overall performance of RPUFs depends on the competition between the positive effects of carbon fibre reinforcement and the negative effects on hydrogen bond formation (28).

A similar decrease in cell size has been reported for the addition of carbon nanotubes to the polyurethane foams (29).

4.3 Thermogravimetric analysis (TGA)

The TGA and Derivative Thermogravimetry (DTG) of carbon fibre powder incorporated RPUF are illustrated in Figures 6a and 6b. To evaluate the thermal stability of these foams TGA is conducted under the flow of nitrogen.

Generally, the thermal stability of RPUFs is described by the degradation onset temperature, i.e. the temperature of 5% weight loss ($T_{5\%}$). Results show a decrease in 5% weight loss temperature ($T_{d5\%}$) from 192°C to 148°C for the foam with 10% concentration of carbon fibre. This behaviour of RPUF is attributed to the increased thermal conductivity of foams, consequently increasing the heat to spread more rapidly only on the percolation path made by the carbon fibre and initializing some initial weight loss (30). Similar decrease in 5% weight loss temperature was observed by Ciecierska et al. on the addition of graphite in RPUF (29). Char residue also increases on increasing the filler concentration. All the samples show three weight loss stages, giving at 195°C, 330°C and 490°C. The beginning slow weight loss stage at 195°C is caused by the initial weight loss of some hard segments around the carbon fibres. Foam with 8% concentration of carbon fibres shows the fastest degradation, which is attributed to better dispersion of carbon fibre consequently providing the longest percolation path for heat transfer. On the other hand, although foam with 10% concentration of carbon fibre possesses a higher concentration of filler, poor dispersion provides comparatively shorter percolation path for heat transfer. The quick weight loss stage at 330°C is related to the degradation of hard segments resulting in the formation of isocyanate, alcohol, amine, olefin and CO_2 . The third slow weight loss stage at 490°C is attributed to the degradation of soft segments and thermolysis of the organic residues. It was observed that the increase in the concentration of filler slows down the degradation up to 8% filler concentration, on increasing the concentration of carbon fibre beyond this limit increases the rate of degradation owing to the poor dispersion of the filler.

Figure 5: SEM micrographs of RPUF with (a) 0% and (b) 8% concentration of carbon fibre powder.

4.4 Cone calorimeter testing

Figures 6c-f show the cone calorimeter performance of RPUF containing a varied concentration of carbon fibre filler and the results are compiled in Table 2. It is evident that the TTIs (time to ignition) of carbon fibre filler incorporated RPUFs have shown a slight increase from 2 s to 5 s for the foams incorporated with 8% carbon fibre powder. Conventionally, the intensity of fire is correlated with the heat release rate (HRR) (31). Results showed that peak heat-release rate (PHRR) were decreased from 118 kW/m² to 85 kW/m² for the foam containing 8% carbon fibre powder (Figure 6c). PHRR signifies the surface pyrolysis of RPUF and evolution of a large quantity of flammable low molecular weight by-products such as primary or secondary amine, isocyanate, alcohol and olefin (32,33). Figure 6d shows that total heat release (THR) also decreases on the incorporation of carbon fibre filler. The char residue increased from 11.5% for neat RPUF to 44.4% for RPUF with 10% carbon fibre powder. Figure 6e shows the smoke production rate (SPR) and the first peak of SPR denotes that the rate of smoke production decreased from 0.008 to 0.004 m²/s for 8% carbon fibre powder loading. The total smoke release (TSR) also decreases from 347 m²/m² to 116 m²/m² on the addition of 8% carbon fibre powder (Figure 6f). This behaviour of RPUF incorporated with carbon fibre powder is associated with the formation of the carbon layer on the surface and consequently reduction in combustion gases, which is analogous to the observations of Ciecierska et al. (29).

4.5 Conductivity measurement

Incorporation of carbon fibre in the RPUF generates conductivity in the foam. Figure 7 shows the change in conductivity of RPUF on the incorporation of carbon fibre.

It is clearly observed by the results that the incorporation of conducting carbon fibre increased the conductivity of RPUFs and the foams with 8% and 10% carbon fibre contents exhibits a conductivity of 1.9×10^{-4} and 7.1×10^{-4} S/m respectively. A similar range of electrical conductivity was obtained by Ibrahim et al. in castor oil-based polyurethane films incorporated with LiI salt (21). So, these foams may be used in the applications where conducting rigid foams are required.

5 Conclusion

RPUFs were prepared by incorporating carbon fibre powder to develop electromagnetic shields using bio-based raw materials. Mechanical, thermal and flame retardant properties of these foam shields have also been studied. FTIR and ¹H NMR spectra of the prepared polyol confirm the transesterification of castor oil. Foams with 8% and 10% carbon fibre concentration show conductivity of 1.9×10^{-4} and 7.1×10^{-4} S/m respectively. Results concluded that RPUF with 8% carbon fibre concentration showed higher mechanical properties with 3-fold increase in compressive and flexural strength respectively. Specific compressive strength was also found to increase by 28% for the

Figure 6: (a) TGA plots, (b) DTG plots, (c) HRR (Heat Release Rate), (d) THR (Total Heat Release), (e) SPR (Smoke Production Rate) and (f) TSR (Total Smoke Release) of RPUFs incorporated with carbon fibre.

foams with 8% concentration of carbon fibre powder. The peak of heat release (PHRR) was found to decrease from 118 kW/m^2 to 85 kW/m^2 on the incorporation of carbon fibre powder. Additionally, the rate of smoke

production was also observed to decrease for composite RPUFs. As the incorporation of carbon fibre in RPUF provides a reasonable amount of conductivity without deteriorating the other properties of vegetable oil based

Table 2: Cone calorimeter data of RPUF incorporated with carbon fibre.

Concentration of filler	PHRR (kW/m ²)	THR (MJ/m ²)	TSR (m ² /m ²)	RESIDUE (%)	TTI (s)
0%	118	29.8	347	11.5	2
2% carbon fibre	99	25.7	144	31.6	3
4% carbon fibre	91	25.3	145	36.1	4
6% carbon fibre	92	19.0	123	40.5	5
8% carbon fibre	85	18.2	116	44.0	5
10% carbon fibre	97	26.0	165	44.4	4

Figure 7: Plots of electrical conductivity(S/m) vs. filler %.

rigid PU foams, so carbon fibres are a potential additive to yield conducting PU foam.

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References

- Nasouri K., Shoushtari A.M., Mojtahedi M.R.M., Theoretical and experimental studies on EMI shielding mechanisms of multi-walled carbon nanotubes reinforced high performance composite nanofibers. *J. Polym. Res.*, 2016, 23(4), 3-10.
- Yan D.X., Pang H., Li B., Vajtai R., Xu L., Ren P.G., et al., Structured reduced graphene oxide/polymer composites for ultra-efficient electromagnetic interference shielding. *Adv. Funct. Mater.*, 2015, 25(4), 559-566.
- Huang Y., Li N., Ma Y., Du F., Li F., He X., et al., The influence of single-walled carbon nanotube structure on the electromagnetic interference shielding efficiency of its epoxy composites. *Carbon*, 2007, 45(8), 1614-1621.
- Aram E., Ehsani M., Khonakdar H.A., Jafari S.H., Nouri N.R., Functionalization of graphene nanosheets and its dispersion in PMMA/PEO blend: Thermal, electrical, morphological and rheological analyses. *Fibers Polym.*, 2016, 17(2), 174-180.
- Tripathi S.N., Saini P., Gupta D., Choudhary V., Electrical and mechanical properties of PMMA/reduced graphene oxide nanocomposites prepared via in situ polymerization. *J. Mater. Sci.*, 2013, 48(18), 6223-6232.
- Stiebra L., Cabulis U., Knite M., Polyurethane foams obtained from residues of PET manufacturing and modified with carbon nanotubes. *J. Phys. Conf. Ser.*, 2016, 709, 012002.
- Yang Y., Gupta M.C., Dudley K.L., Lawrence R.W., Novel carbon nanotube - Polystyrene foam composites for electromagnetic interference shielding. *Nano. Lett.*, 2005, 5(11), 2131-2134.
- Ameli A., Jung P.U., Park C.B., Electrical properties and electromagnetic interference shielding effectiveness of polypropylene/carbon fiber composite foams. *Carbon*, 2013, 60, 379-391.
- Kuang T., Chang L., Chen F., Sheng Y., Fu D., Peng X., Facile preparation of lightweight high-strength biodegradable polymer/multi-walled carbon nanotubes nanocomposite foams for electromagnetic interference shielding. *Carbon*, 2016, 105, 305-313.
- Li J., Zhang G., Zhang H., Fan X., Zhou L., Shang Z., et al., Applied Surface Science Electrical conductivity and electromagnetic interference shielding of epoxy nanocomposite foams containing functionalized multi-wall carbon nanotubes. *Appl. Surf. Sci.*, 2018, 428, 7-16.
- Hwang S., Tensile, electrical conductivity and EMI shielding properties of solid and foamed PBT/carbon fiber composites. *Compos. Part B-Eng.*, 2016, 98, 1-8. DOI:10.1016/j.compositesb.2016.05.028
- Zhang H., Zhang G., Li J., Fan X., Jing Z., Li J., et al., Lightweight, multifunctional microcellular PMMA/Fe₃O₄ @ MWCNTs nanocomposite foams with efficient electromagnetic interference shielding. *Compos. Part A-Appl. S.*, 2017, 100, 128-138.
- Li Y., Shen B., Pei X., Zhang Y., Yi D., Zhai W., et al., Ultrathin carbon foams for effective electromagnetic interference shielding. *Carbon*, 2016, 100, 375-385.
- Li Y., Shen B., Yi D., Zhang L., Zhai W., Wei X., et al., The influence of gradient and sandwich configurations on the electromagnetic interference shielding performance of multilayered thermoplastic polyurethane/graphene composite foams. *Compos. Sci. Technol.*, 2017, 138, 209-216.
- Farhan S., Wang R., Li K., Electromagnetic interference shielding effectiveness of carbon foam containing in situ grown silicon carbide nanowires. *Ceram. Int.*, 2016, 42(9), 11330-11340.
- Nasr Esfahani A., Katbab A.A., Taeb A., Simon L., Pope M.A., Correlation between mechanical dissipation and improved X-band electromagnetic shielding capabilities of amine functionalized graphene/thermoplastic polyurethane composites. *Eur. Polym. J.*, 2017, 95, 520-538.

17. Stirna U., Cabulis U., Beverte I., Water-Blown Polyisocyanurate Foams from Vegetable oil polyols. *J. Cell. Plast.*, 2008, 44, 139-160.
18. Malik M., Kaur R., Mechanical and Thermal Properties of Castor Oil-Based Polyurethane Adhesive: Effect of TiO_2 Filler. *Adv. Polym. Technol.*, 2016, 1-7.
19. Malik M., Kaur R., Synthesis of NIPU by the carbonation of canola oil using highly efficient 5,10,15-tris(pentafluorophenyl) corrolato-manganese (III) complex as novel catalyst. *Polym. Adv. Technol.*, 2018, 29(3), 1078-1085.
20. Malik M., Kaur R., Influence of aliphatic and aromatic isocyanates on the properties of poly(ether ester) polyol based PU adhesive system. *Polym. Eng. Sci.*, 2018, 58(1), 112-117.
21. Ibrahim S., Ahmad A., Mohamed N.S., Synthesis and characterization of castor oil-based polyurethane for potential application as host in polymer electrolytes. *B. Mater. Sci.*, 2015, 38(5), 1155-1161.
22. Kaur R., Kumar M., Function of silicon oil in the castor oil based rigid polyurethane foams. *J. Polym. Eng.*, 2013, 33(9), 875-880.
23. Kumar M., Kaur R., Glass fiber reinforced rigid polyurethane foam: synthesis and characterization. *e- Polymers*, 2017, 17(6), 517-521.
24. Kaur R., Effect of Fillers on the Mechanical Properties of Castor Oil Bases Rigid Polyurethane Foams. *Int. J. Res. Rev.*, 2018, 7(2), 296-302.
25. Agrawal A., Kaur R., Walia R.S., PU foam derived from renewable sources: Perspective on properties enhancement: An overview. *Eur. Polym. J.*, 2017, 95, 255-274.
26. Narwal S.K., Saun N.K., Dogra P., Chauhan G., Gupta R., Production and Characterization of Biodiesel Using Nonedible Castor Oil by Immobilized Lipase from *Bacillus aerius*. *Biomed. Res. Int.*, 2015, 281934, 1-6.
27. Hejna A., Kirpluks M., Kosmela P., Cabulis U., Haponiuk J., The influence of crude glycerol and castor oil-based polyol on the structure and performance of rigid polyurethane-polyisocyanurate foams. *Ind. Crop. Prod.*, 2017, 95, 113-125.
28. Cao X., James Lee L., Widya T., Macosko C., Polyurethane/clay nanocomposites foams: Processing, structure and properties. *Polymer*, 2005, 46(3), 775-783.
29. Ciecierska E., Jurczyk-Kowalska M., Bazarnik P., Gloc M., Kulesza M., Kowalski M., et al., Flammability, mechanical properties and structure of rigid polyurethane foams with different types of carbon reinforcing materials. *Compos. Struct.*, 2016, 140, 67-76.
30. Luyt A.S., Molefi J.A., Krump H., Thermal, mechanical and electrical properties of copper powder filled low-density and linear low-density polyethylene composites. *Polym. Degrad. Stab.*, 2006, 91(7), 1629-1636.
31. Wang Y., Wang F., Dong Q., Xie M., Liu P., Ding Y., et al., Core-shell expandable graphite @ aluminum hydroxide as a flame-retardant for rigid polyurethane foams. *Polym. Degrad. Stab.*, 2017, 146, 267-276.
32. Zhang M., Zhang J., Chen S., Zhou Y., Synthesis and fire properties of rigid polyurethane foams made from a polyol derived from melamine and cardanol. *Polym. Degrad. Stab.*, 2014, 110, 27-34.
33. Yang R., Wang B., Han X., Ma B., Li J., Synthesis and characterization of flame retardant rigid polyurethane foam based on a reactive flame retardant containing phosphazene and cyclophosphonate. *Polym. Degrad. Stab.*, 2017, 144, 62-69.