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Shielding effectiveness of carbon-filled polycarbonate composites

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ABSTRACT: In this project, varying amounts of three different carbons [carbon black (CB), carbon nanotubes (CNT), and graphene nanoplatelets (GNP)] were added to polycarbonate (PC). The resulting single filler composites were tested for shielding effectiveness (SE). The effects of single fillers and combinations of two different carbon fillers were studied via a factorial design. At the highest single filler loadings, the following SE results were obtained at 800 MHz: 18.9 dB for 10 wt % CB/PC, 18.4 dB for 8 wt % CNT/PC, and 6.3 dB for 15 wt % GNP/PC. The highest SE value of 21.4 dB was measured for the 5 wt % CB/5 wt % CNT/PC composite and could be used in SE applications (typically > 20 dB is needed). Statistically significant equations were developed that could be used to predict the SE of composites containing these fillers. In addition, it was determined that the composite SE is higher than what would be expected from the additive effect of each single filler for the CB/GNP/PC composites. © 2015 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2015**, *132*, 42719.

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INTRODUCTION

Adding electrically conductive fillers to insulating polymers can increase the electrical conductivity of the resulting composite. In many cases, if the electrical resistivity (ER = 1/electrical conductivity) of the composite ≤ 10 ohm-cm, it can be used for electromagnetic interference (EMI)/radio frequency interference (RFI) shielding applications.[1] Electrical energy is emitted by electronic devices. A common practice is to cover the electronic device with a shielding material to prevent it from emitting electromagnetic or radio frequency energy. The shielding material either reflects or absorbs the electromagnetic energy within the material.[2] Shielding effectiveness (SE) is defined as the ratio of the power received with and without a material present and is shown below.[3]

$$\text{SE, dB} = 10 \log (P_1/P_2) \tag{1}$$

where P_1 = received power with the material present P_2 = received power without the material present

A material that reflects and/or absorbs 99% of the electromagnetic (EM) energy has a SE of 20 and may be used for shielding applications.[4]

Polycarbonate is a good matrix material to use for shielding applications due to its high impact strength at temperatures between −40°C and 100°C. In the open literature, several researchers have studied the effect of adding carbon fibers, nickel coated carbon fibers, and carbon nanotubes (CNT) to polycarbonate (PC) and measured the composite electrical conductivity and SE. Specifically, Bushko *et al.* showed reported a SE of 35 dB for a polycarbonate composite containing 24 wt % carbon fiber[4] and Murthy *et al.* reported a SE of 35 dB for a polycarbonate composite containing 10 wt % nickel coated carbon fiber.[5] The effect of carbon nanotubes has been investigated by Arjmand *et al.* and they measured a SE of ~22 dB for a polycarbonate composite containing 5 wt % carbon nanotubes.[6] Carbon black (CB) and graphene nanoplatelets (GNP) can also be used to produce electrically conductive composites.[7–12]

In this project, our research group extruded, injection molded, conducted ER and SE testing of carbon-filled polycarbonate composites. The three carbon fillers investigated included an electrically conductive carbon black, graphene nanoplatelets, and multiwalled carbon nanotubes. Materials were fabricated and tested which contained varying amounts of these single carbon fillers. Composites containing combinations of two of these different fillers were also fabricated and tested. There were two objectives for this study. The first was to find the effects and

Table I. Filler Properties[10,12–16]

Ketjenblack EC-600 JD Carbon Black (CB)	
Density	1.8 g/cc
BET (N_2) surface area	1250 m^2/g
Fibril™ carbon nanotubes (CNT)	
Density	2.0 g/cc nanotube wall; 1.75 g/cc hollow nanotube
BET (N_2) surface area	250 m^2/g
Graphene nanoplatelets (GNP)	
Density	2.0 g/cc
BET (N_2) surface area	130 m^2/g

interactions of each carbon filler on the composite SE. The second was to develop equations that relate composite SE to the amount of each conductive filler in the composite. ER test methods and results will also be reported here since these results provide an indication of SE. Per the authors' knowledge, the SE of these combinations of carbon fillers (CB, CNT, and GNP) in polycarbonate has not been previously reported in the open literature.

MATERIALS AND EXPERIMENTAL METHODS

Materials

The materials used in the project are described in more detail in a previous paper by our research group. Sabic's Lexan HF1130-111 polycarbonate was used. Table I lists the properties of the fillers used in this study.[10,12–16] Akzo Nobel's electrically conductive carbon black Ketjenblack EC-600 JD was used. Hyperion's FIBRIL™ multi-walled carbon nanotubes, which have an aspect ratio of 1000,[14] were used in a 15 wt % FIBRIL™ masterbatch MB6015-00 in polycarbonate. Graphene nanoplatelets obtained from Ovation Polymers as Extima™ MB PC1515A were the last carbon filler investigated. Extima™ MB PC1515A contains 15 wt % xGnP™ (from XG Sciences: 5 μm average particle diameter and a thickness of 6−8 nm) embedded in polycarbonate.[12]

Table II shows the concentrations in wt % and vol % of the single filler composites studied in this project. A maximum of 10 wt % CB, 8 wt % CNT, and 15 wt % GNP were used since above these levels the composite melt viscosity was too high to allow the material to be extruded and injection molded. Table II also shows the SE at 800 MHz and ER (1/electrical conductivity) results that will be described later in this manuscript.[17] Table III shows the SE at 800 MHz and ER results for composites containing combinations of two different fillers.[18] Due to composite melt viscosity and cost (for CNT) constraints, the following filler loading levels were chosen for the composites containing combinations of fillers: 2 and 5 wt % for CB, 1 and 5 wt % for CNT, and 2 and 5 wt % for GNP. ER results for these polycarbonate based formulations were previously reported by our research group.

Test Specimen Fabrication

The materials used for this project were previously extruded by our research group using an American Leistritz Extruder Corporation 27 mm corotating intermeshing twin screw extruder. Additional information concerning extrusion conditions are found elsewhere.[19] A Niigata single screw injection molding machine, model NE85UA$_4$, was used to produce test specimens needed for this project. End gated 3.3 mm thick ASTM Type I tensile bars and 6.4 cm diameter disks (used for ER tests) were fabricated using a four cavity mold. A single cavity mold was used to produce end gated 13.1 cm diameter disks (3.2 mm thick) which were the SE test specimens.

Transmission Electron Microscope (TEM) Test Method

A Leica UCT/FCS cryo-ultramicrotome and a Diatome 35° Cryo-Dry diamond knife was used to prepare injection molded composite samples for the JEOL JEM-2010 transmission electron microscope. A Gatan Orius camera was used to collect digital images.

Electrical Resistivity (ER) Test Methods

Two different ER test methods were used at 23°C. For formulations with an ER $> 10^6$ ohm-cm, the volumetric electrical conductivity test was conducted according to ASTM D257 using a Keithley 6517A Electrometer/High Resistance Meter and an 8009 Resistivity Test Fixture.[20] If the ER $< 10^6$ ohm-cm, it was measured using ASTM D 4496.[21] Additional details concerning ER test methods were previously reported by our research group and are shown elsewhere.[17]

Shielding Effectiveness (SE) Test Method

ASTM D 4935 was used to measure the electromagnetic (EM) shielding effectiveness (SE) of each formulation over the frequency range of 300 MHz to 1.5 GHz using an Electro-Metrics, Inc. model EM-2107A shielding effectiveness test fixture.[3] A Rhodes & Schwarz ZVL network analyzer was used to generate (1 mW of input power) and receive signals. The tests were conducted inside a Faraday cage to minimize interference. Prior to testing, the SE samples were conditioned at 23°C and 50% relative humidity for 2 days. For each formulation, one reference sample and six load samples were tested. The SE of a formulation was the SE of the reference sample subtracted from the SE of the load sample. The largest difference between the maximum and minimum signals measurable by our test fixture was 80 dB.

RESULTS

Transmission Electron Microscope (TEM) Results

Figure 1(a,b) show TEM images of the composites containing 5 wt % CB and 5 wt % CNT in PC and 5 wt % CNT and 5 wt % GNP in PC, respectively. All three different fillers are shown in these figures. The high aspect ratio of the CNT is evident in Figure 1(a). Figure 1(b) shows the platelet shape of the GNP.

Shielding Effectiveness (SE) Results

Single Fillers. Figure 2 shows the mean transmitted, reflected, and absorbed power versus frequency for the composite containing 8 wt % (5.5 vol %) CB in PC. The supplied (incident) power was 1 mW. Figure 2 shows that at 800 MHz, the transmitted power is ~0.01 mW. The mean SE results for the composites containing varying amounts of carbon black (CB) in polycarbonate (PC) are shown in Figure 3. The SE values range from 0 dB for the neat PC to 18.9 dB at 800 MHz for the 10

Table II. Single Filler Loading Levels in Polycarbonate and Shielding Effectiveness and Electrical Resistivity Results[17]

Formulation	Filler wt %	Filler vol %	Electrical resistivity (ohm cm)	SE at 800 MHz (dB)
PC	0	0.0	$1.3 \times 10^{17} \pm 3.3 \times 10^{16}$ $n = 6$	0.06 ± 0.007 $n = 6$
PC replicate	0	0.0	$9.4 \times 10^{16} \pm 2.0 \times 10^{16}$ $n = 6$	0.09 ± 0.003 $n = 6$
2CB	2	1.34	$4.0 \times 10^{16} \pm 2.7 \times 10^{16}$ $n = 6$	0.42 ± 0.03 $n = 6$
2CB replicate	2	1.34	$2.4 \times 10^{16} \pm 1.3 \times 10^{16}$ $n = 6$	0.30 ± 0.02 $n = 6$
3CB	3	2.01	$2.8 \times 10^{15} \pm 4.6 \times 10^{14}$ $n = 6$	1.61 ± 0.04 $n = 6$
4CB	4	2.69	$1.2 \times 10^{5} \pm 7.8 \times 10^{4}$ $n = 8$	3.37 ± 0.01 $n = 6$
5CB	5	3.38	3920 ± 230 $n = 8$	5.83 ± 0.02 $n = 6$
5CB replicate	5	3.38	3970 ± 280 $n = 8$	5.87 ± 0.05 $n = 6$
6CB	6	4.07	649 ± 18 $n = 8$	7.77 ± 0.06 $n = 6$
8CB	8	5.46	122 ± 4 $n = 8$	13.27 ± 0.07 $n = 6$
10CB	10	6.88	19.5 ± 0.5 $n = 8$	18.90 ± 0.09 $n = 6$
0.5CNT	0.5	0.34	$6.2 \times 10^{16} \pm 1.2 \times 10^{16}$ $n = 6$	0.09 ± 0.02 $n = 6$
1CNT	1	0.69	$2.0 \times 10^{16} \pm 7.5 \times 10^{15}$ $n = 6$	0.38 ± 0.01 $n = 6$
1CNT replicate	1	0.69	$2.0 \times 10^{16} \pm 6.6 \times 10^{15}$ $n = 6$	0.38 ± 0.01 $n = 6$
2CNT	2	1.38	4610 ± 1120 $n = 6$	2.94 ± 0.03 $n = 6$
3CNT	3	2.08	938 ± 230 $n = 5$	8.02 ± 0.02 $n = 6$
4CNT	4	2.78	489 ± 37 $n = 5$	11.50 ± 0.23 $n = 6$
5CNT	5	3.48	163 ± 9 $n = 6$	14.35 ± 0.18 $n = 6$
5CNT replicate	5	3.48	177 ± 16 $n = 6$	14.45 ± 0.17 $n = 6$
6CNT	6	4.19	18 ± 2 $n = 6$	15.78 ± 0.11 $n = 6$
8CNT	8	5.63	7.8 ± 0.4 $n = 6$	18.44 ± 0.28 $n = 6$
2GNP	2	1.21	$5.5 \times 10^{16} \pm 4.9 \times 10^{15}$ $n = 6$	0.25 ± 0.01 $n = 6$
2GNP replicate	2	1.21	$5.2 \times 10^{16} \pm 2.2 \times 10^{16}$ $n = 6$	0.22 ± 0.01 $n = 6$
3GNP	3	1.82	$3.2 \times 10^{16} \pm 7.2 \times 10^{15}$ $n = 8$	0.37 ± 0.01 $n = 6$
4GNP	4	2.44	$1.2 \times 10^{16} \pm 3.5 \times 10^{14}$ $n = 6$	0.47 ± 0.01 $n = 6$
5GNP	5	3.06	$3.8 \times 10^{15} \pm 5.6 \times 10^{14}$ $n = 6$	0.68 ± 0.02 $n = 6$
5GNP replicate	5	3.06	$3.8 \times 10^{15} \pm 2.8 \times 10^{14}$ $n = 6$	0.68 ± 0.02 $n = 6$
6GNP	6	3.69	$2.0 \times 10^{14} \pm 5.0 \times 10^{12}$ $n = 6$	1.05 ± 0.02 $n = 6$
8GNP	8	4.96	$3.9 \times 10^{7} \pm 1.5 \times 10^{7}$ $n = 8$	1.71 ± 0.01 $n = 6$
10GNP	10	6.25	$1.7 \times 10^{6} \pm 2.6 \times 10^{5}$ $n = 8$	2.69 ± 0.03 $n = 6$
12GNP	12	7.56	$3.1 \times 10^{5} \pm 9.5 \times 10^{3}$ $n = 5$	3.99 ± 0.08 $n = 6$
15GNP	15	9.57	$2.8 \times 10^{4} \pm 8.3 \times 10^{3}$ $n = 8$	6.28 ± 0.11 $n = 6$

wt % (6.9 vol %) CB/ PC composite. The authors have previously reported a SE of ~22 dB at 800 MHz for 10 wt % (6.9 vol %) for this CB in a different polycarbonate and produced with a different extruder screw design.[22] This value of ~22 dB is similar to our current results of ~19 dB. This prior work investigated the effects on SE of polycarbonate based composites containing CB, carbon fiber, and synthetic graphite particles. This current work studies the composite SE of polycarbonate based composites containing CB, CNT, and GNP. Figure 4 shows the mean power (absorbed, reflected, transmitted, and incident) versus amount of carbon black at 800 MHz. "Lines" are shown in this and similar figures to help the reader follow the trends. For most of the CB/PC composites, absorption is the primary SE mechanism. At the highest filled composite (10 wt % CB/90 wt % PC), the power reflected was greater than the power absorbed.

It is interesting to compare the ER and SE results for the CB/PC composites. The pure PC had a mean ER of 1×10^{17} ohm-cm. As noted in Table II, the percolation threshold occurred at ~2.3 vol % (3.5 wt %) CB. The percolation threshold is defined as the point where adding a small amount of conductive filler dramatically increases the composite electrical conductivity (reduces composite ER = 1/electrical conductivity). Figure 5 shows the mean SE at 800 MHz and the mean log ER as a function of the amount of CB in polycarbonate (PC). Once again, lines are shown in this and similar figures to help the reader follow the trends. As expected, below the percolation threshold, the SE is very low (<3 dB). Above the percolation threshold, the SE increases as EC increases (ER decreases). The addition of the highly branched CB structure causes a large decrease in composite ER and a resulting increase in SE by absorbing and/ or reflecting EMI/RFI energy.

Table III. Combinations of Different Fillers: Shielding Effectiveness and Electrical Resistivity Results[18]

Formulations	Constituents			Electrical resistivity (ohm cm)	SE at 800 MHz (dB)
2CB*1CNT		wt %	vol %		3.7 ± 0.14 $n = 6$
Original	CB	2	1.3	$2.5 \times 10^5 \pm 5.3 \times 10^4$ $n = 6$	3.7 ± 0.11 $n = 6$
Replicate	CNT	1	0.7	$2.9 \times 10^5 \pm 7.3 \times 10^4$ $n = 6$	
	PC	97	98		
2CB*5CNT		wt %	vol %		15.7 ± 0.1 $n = 6$
Original	CB	2	1.4	74 ± 3 $n = 6$	15.7 ± 0.1 $n = 6$
Replicate	CNT	5	3.5	69 ± 2 $n = 6$	
	PC	93	95.1		
5CB*1CNT		wt %	vol %		9.8 ± 0.1 $n = 6$
Original	CB	5	3.4	433 ± 9 $n = 4$	9.7 ± 0.1 $n = 6$
Replicate	CNT	1	0.7	430 ± 7 $n = 4$	
	PC	94	95.9		
5CB*5CNT		wt %	vol %		21.2 ± 0.3 $n = 6$
Original	CB	5	3.5	15.9 ± 0.5 $n = 6$	21.7 ± 0.1 $n = 6$
Replicate	CNT	5	3.5	14.9 ± 0.5 $n = 7$	
	PC	90	93		
2CB*2GNP		Wt %	Vol %		1.0 ± 0.1 $n = 6$
Original	CB	2	1.4	$4.0 \times 10^{15} \pm 9.2 \times 10^{14}$ $n = 6$	1.0 ± 0.1 $n = 6$
Replicate	GNP	2	1.2	$3.8 \times 10^{15} \pm 1.3 \times 10^{15}$ $n = 6$	
	PC	96	97.4		
2CB*5GNP		wt %	vol %		2.1 ± 0.1 $n = 6$
Original	CB	2	1.4	$2.4 \times 10^7 \pm 3.1 \times 10^6$ $n = 5$	2.3 ± 0.1 $n = 6$
Replicate	GNP	5	3.1	$1.8 \times 10^7 \pm 4.3 \times 10^6$ $n = 4$	
	PC	93	95.5		
5CB*2GNP		wt %	vol %		6.5 ± 0.4 $n = 6$
Original	CB	5	3.4	1337 ± 16 $n = 6$	6.7 ± 0.3 $n = 6$
Replicate	GNP	2	1.2	1387 ± 32 $n = 5$	
	PC	93	95.4		
5CB*5GNP		wt %	vol %		9.2 ± 0.2 $n = 6$
Original	CB	5	3.5	729 ± 42 $n = 5$	9.3 ± 0.2 $n = 6$
Replicate	GNP	5	3.1	735 ± 40 $n = 5$	
	PC	90	93.4		
1CNT* 2GNP		wt %	vol %		0.82 ± 0.04 $n = 6$
Original	CNT	1	0.7	$4.1 \times 10^{15} \pm 1.6 \times 10^{15}$ $n = 7$	0.81 ± 0.04 $n = 6$
Replicate	GNP	2	1.2	$5.0 \times 10^{15} \pm 1.8 \times 10^{15}$ $n = 6$	
	PC	97	98.1		
1CNT* 5GNP		wt %	vol %		1.8 ± 0.1 $n = 6$
Original	CNT	1	0.7	$6.2 \times 10^6 \pm 1.3 \times 10^6$ $n = 4$	1.9 ± 0.1 $n = 6$
Replicate	GNP	5	3.1	$6.4 \times 10^6 \pm 9.0 \times 10^5$ $n = 4$	
	PC	94	96.2		
5CNT* 2GNP		wt %	vol %		13.7 ± 0.1 $n = 6$
Original	CNT	5	3.5	210 ± 5 $n = 7$	13.7 ± 0.1 $n = 6$
Replicate	GNP	2	1.2	198 ± 6 $n = 6$	
	PC	93	95.3		
5CNT* 5GNP		wt %	vol %		15.5 ± 0.1 $n = 6$
Original	CNT	5	3.6	126 ± 11 $n = 6$	15.6 ± 0.1 $n = 6$
Replicate	GNP	5	3.1	128 ± 9 $n = 6$	
	PC	90	93.3		

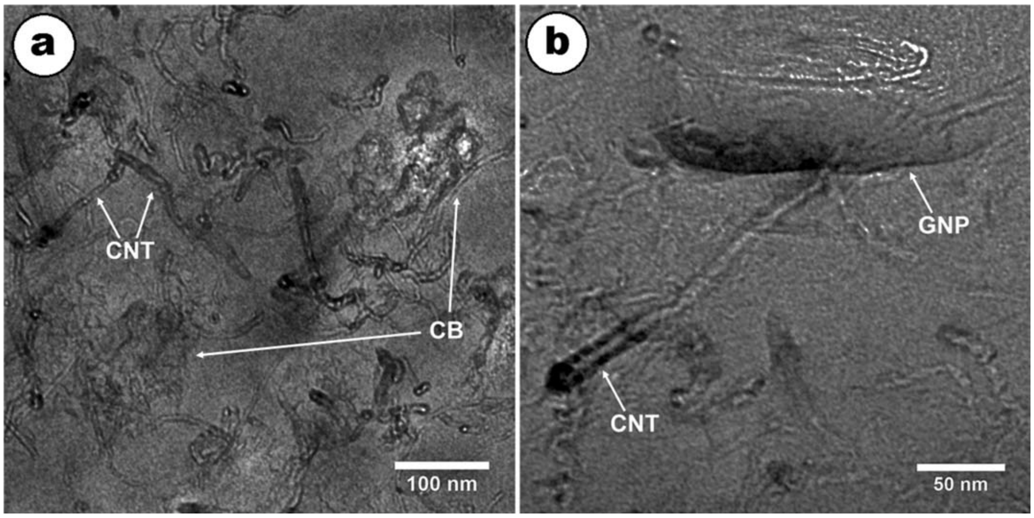

Figure 1. TEM images of (a) 5 wt % CB/5 wt % CNT/90 wt % PC composite and (b) 5 wt % CNT/5% GNP/90 wt % PC composite.

The mean SE results for the composites containing varying amounts of carbon nanotubes (CNT) in polycarbonate (PC) are shown in Figure 6. The SE values range from 0 dB for the pure PC to 18.4 dB at 800 MHz for the 8 wt % (5.6 vol %) CNT/PC composite. As mentioned earlier in this article, Arjmand *et al.* reported a SE of ∼22 dB for a compression molded 5 wt % CNT/95 wt % PC composite.[6] The ER of a compression molded composite is often lower than that of an injection-molded composite, which could account for the higher SE observed by Arjmand *et al.* Figure 7 shows the mean power (absorbed, reflected, transmitted, and incident) versus amount of CNT at 800 MHz. For most of the CNT/PC composites, absorption is the primary SE mechanism. For composites containing 8 wt % (5.6 vol %) CNT, the power reflected was greater than the power absorbed. Table II shows that the percolation threshold occurred at ∼0.8 vol % (1.2 wt %) CNT. Figure 8 shows SE at 800 MHz and log ER for the CNT/PC composites. By comparing the SE (13.3 dB) of the 8 wt % (5.5 vol %) CB/92 wt % PC with the SE (18.4 dB) of 8 wt % (5.6 vol %) CNT/92 wt % PC, one notices that the highest aspect ratio filler (CNT) produces a higher SE material by absorbing and/or reflecting more EMI/RFI energy.

The mean SE results for the composites containing varying amounts of GNP in polycarbonate (PC) are shown in Figure 9. The SE values range from 0 dB for the pure PC to 6.3 dB at 800 MHz for the 15 wt % (9.6 vol %) GNP/PC composite. The SE values for the composites containing less than 4 wt % GNP are not shown since their SE values were very low. Figure 10 shows the mean power (absorbed, reflected, transmitted, and incident) versus amount of GNP at 800 MHz. For most of the GNP/PC composites, absorption is the primary SE mechanism. For composites containing > 10 wt % (6.3 vol %) GNP, the power reflected was greater than the power absorbed. Table II shows the percolation threshold occurs ∼4 vol % (7 wt %) GNP. Figure 11 shows the mean SE at 800 MHz and the mean log ER for GNP/PC composites.[17] Once again, below the percolation threshold, SE is low (<2 dB). Above the threshold, as ER decreases, SE increases. For the GNP/PC composites, Figure 11 shows a lower composite SE and corresponding higher ER as compared to a similar volume fraction of CB and CNT (see

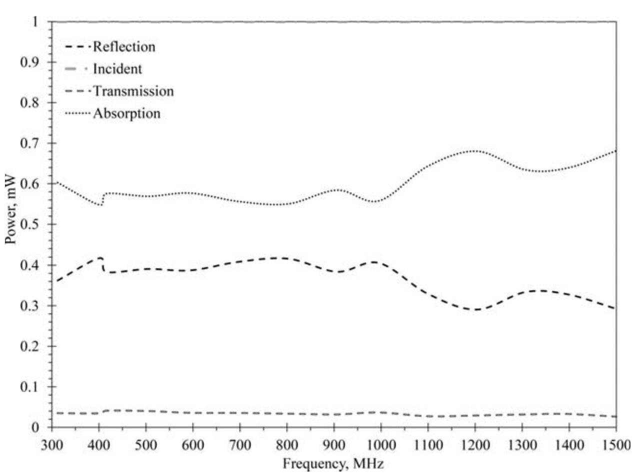

Figure 2. Reflected, absorbed, transmitted, and incident power for 8 wt % carbon black/92 wt % polycarbonate composite.

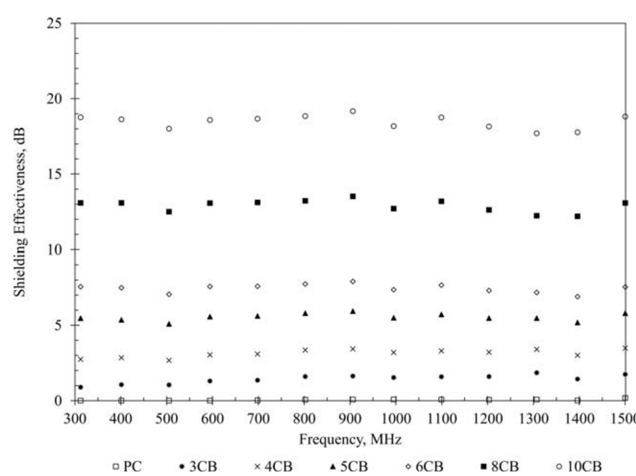

Figure 3. Shielding effectiveness of carbon black/polycarbonate composites.

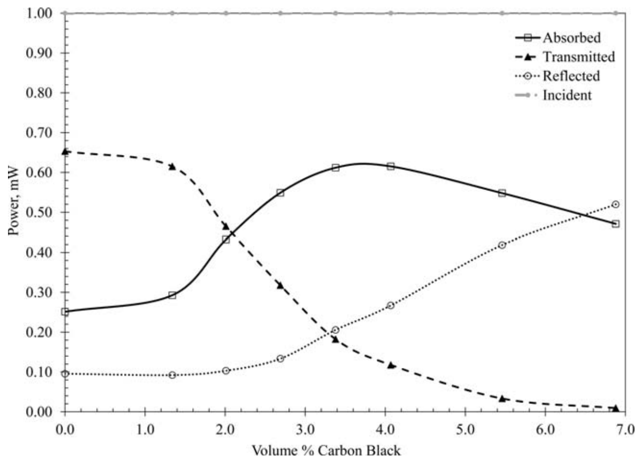

Figure 4. Reflected, absorbed, transmitted, and incident power at 800 MHz for carbon black/polycarbonate composites.

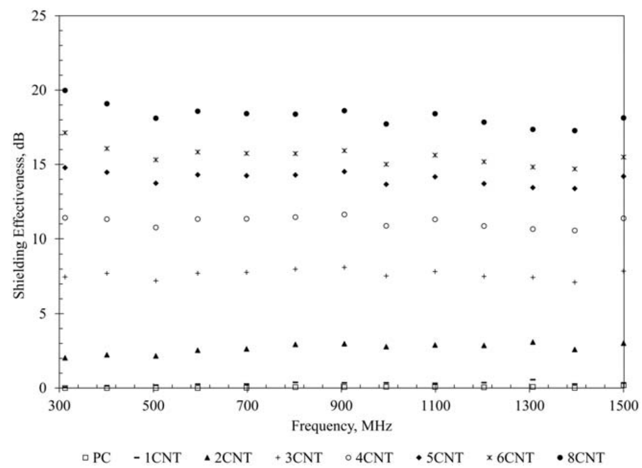

Figure 6. Shielding effectiveness of carbon nanotube/polycarbonate composites.

Figures 5 and 8). The platelet structure of the GNP has a lower aspect ratio as compared to CNT. CB's highly branched structure allows the composite to have high SE and low ER as a result of adding relatively small amounts of CB.

Combinations of Two Different Fillers

Combinations of different amounts of two different carbon fillers were fabricated and tested. Table III shows the mean, standard deviation, and number of specimens tested for SE at 800 MHz for these formulations (original and replicate). Relatively low amounts of each carbon filler was used to ensure that the resulting composite could be extruded and injection molded since high CB amounts, in particular, are known to dramatically increase composite melt viscosity. Also, adding a large amount of CNT will dramatically increase the composite cost. The filler structure appears to play a large role in the composite SE. For example, composites containing the highly branched CB and high aspect ratio CNT had the highest SE.

Table IV shows the coefficients, *t*-statistics (calculated by dividing the estimated SE by the estimated SE standard error), and associated *P*-values. Large absolute values for *t* and associated small *P*-values indicate that a carbon filler may have a significant effect on SE. The larger the absolute *t* value, the more effect the filler has on the composite SE. A significance level, α, of 0.05 was used.

For the CB/CNT composites, the single filler of CB and the single filler of CNT caused a statistically significant increase in SE. This effect is best described by a quadratic term for CB indicating a larger effect as more CB is added.

$$\mathrm{SE}(dB) = -0.947 + 0.2289 w_{\mathrm{CB}}^2 + 3.0557 w_{\mathrm{CNT}} \qquad R^2 = 0.99 \quad (2)$$

where w_{CB} and w_{CNT} are the weight percentages of CB and CNT, respectively. Adding highly branched CB to the already high aspect ratio CNT did not significantly affect the composite SE.

For the CB/GNP composites, the single filler of CB and GNP and the interaction of both of these fillers caused a statistically significant increase in SE, as shown in the equation below.

$$\mathrm{SE}(dB) = -0.4492 w_{\mathrm{CB}} + 0.3153 w_{\mathrm{CB}}^2 + 0.02849 w_{\mathrm{GNP}}^2 + 0.11051 w_{\mathrm{CB}} w_{\mathrm{GNP}} \qquad R^2 = 1.0 \quad (3)$$

where w_{CB} and w_{GNP} are the weight percentages of CB and GNP, respectively. This statistically significant interaction term

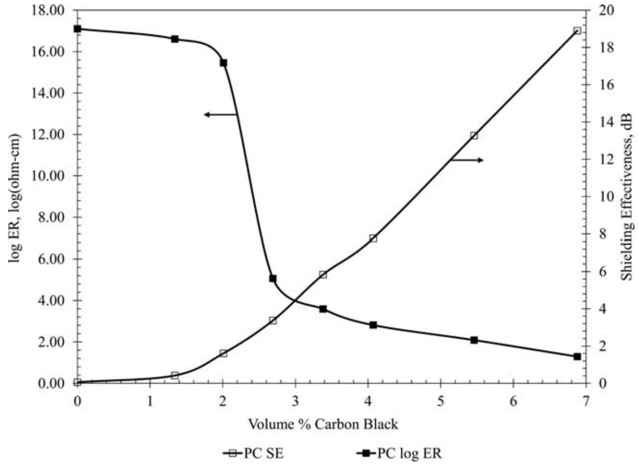

Figure 5. Shielding effectiveness (dB) and log (electrical resistivity, ohm-cm) results for carbon black/polycarbonate composites.

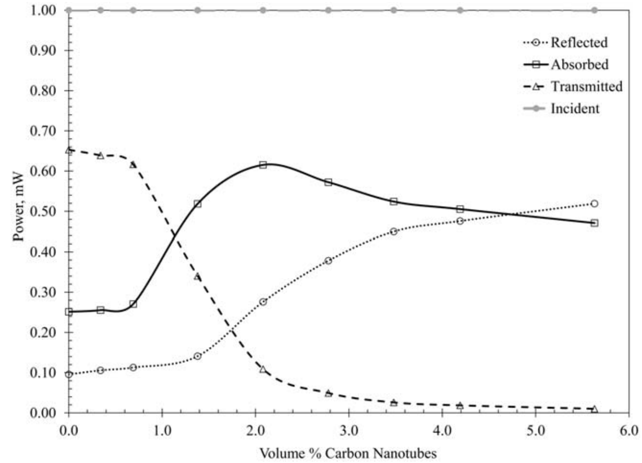

Figure 7. Reflected, absorbed, transmitted, and incident power at 800 MHz for carbon nanotube/polycarbonate composites.

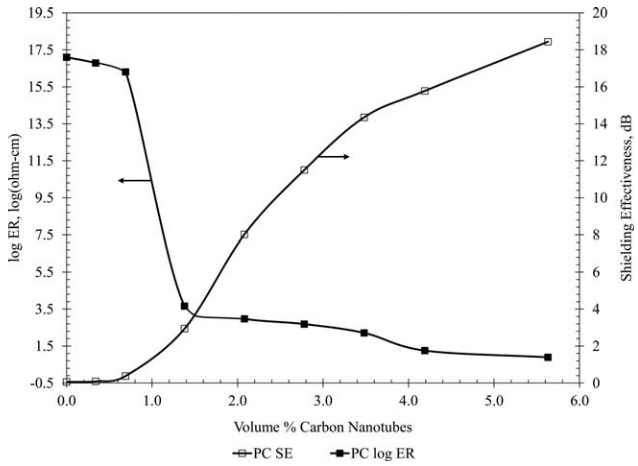

Figure 8. Shielding effectiveness (dB) and log (electrical resistivity, ohm-cm) results for carbon nanotube/polycarbonate composites.

implies that when CB and GNP are combined, the composite SE is higher (positive coefficient) than what would be expected from the additive effect of each single filler. Per the authors' knowledge, this is the first time in the open literature that this synergistic effect has been reported. It appears that adding even small amounts of the highly branched CB to the platelet GNP structure causes a statistically significant increase in composite SE by absorbing and/or reflecting additional EMI/RFI energy.

For the CNT/GNP composites, the single filler of CNT and GNP caused a statistically significant increase in SE, as shown in the equation below. For this system, there is a not a statistically significant effect on SE from the combination of CNT and GNP. Apparently, adding the highly branched CB to GNP caused the composite SE to increase more than adding the high aspect ratio CNT.

$$SE(dB)=0.56627w_{CNT}^2+0.04642w_{GNP}^2 \qquad R^2=1.0 \qquad (4)$$

For all three composite systems, the R^2 values ($\geq$0.99) are excellent and indicate that the majority of the variation in the data is accounted for by the models. Equations (2) to (4) could be used to predict the composite SE.

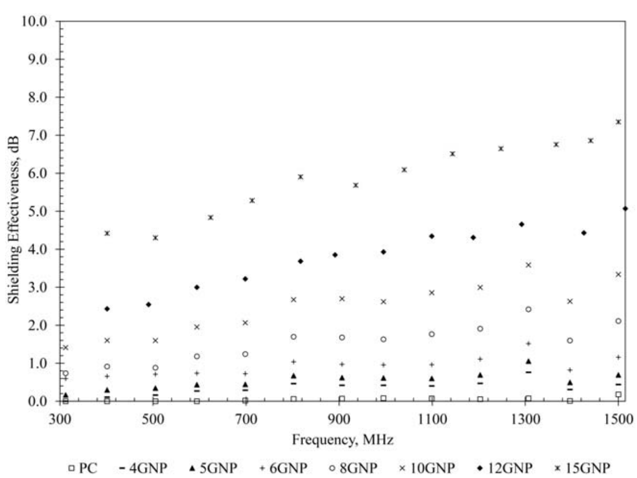

Figure 9. Shielding effectiveness of graphene nanoplatlet/polycarbonate composites.

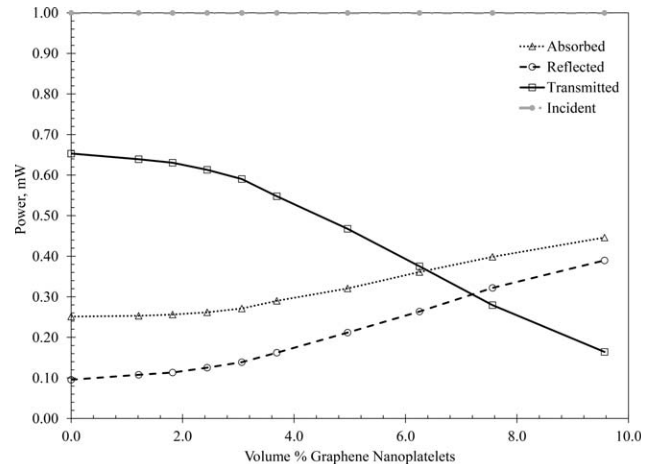

Figure 10. Reflected, absorbed, transmitted, and incident power at 800 MHz for graphene nanoplatlet/polycarbonate composites.

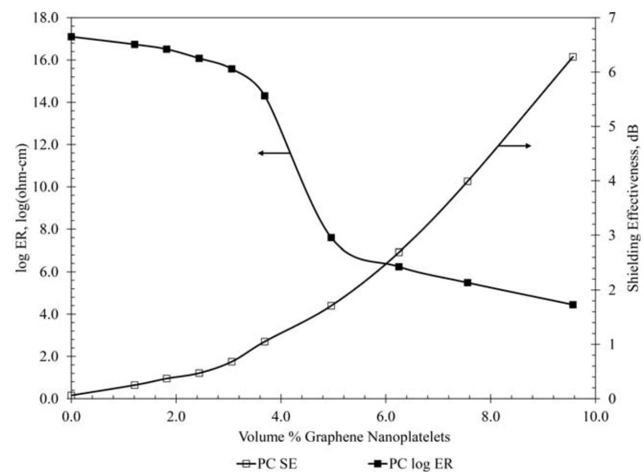

Figure 11. Shielding effectiveness (dB) and log (electrical resistivity, ohm-cm) results for graphene nanoplatelet/polycarbonate composites.

Table IV. 3^2 Regression Results for SE (dB)

Model term	Coefficient	*t*	*p*
Model for CB/CNT composites			
Constant	−0.9470	−3.13	0.007
CB^2	0.2289	17.02	0.000
CNT	3.0557	35.48	0.000
Model for CB/GNP composites			
CB	−0.4492	−6.13	0.000
CB^2	0.3153	23.82	0.000
GNP^2	0.02849	5.78	0.000
CB*GNP	0.11051	13.07	0.000
Model for CNT/GNP composites			
CNT^2	0.56627	86.93	0.000
GNP^2	0.04642	6.76	0.000

CONCLUSIONS

The object of this research was to determine the effects and interactions of each filler on composite SE and to develop equations that can be used to relate composite SE to the weight fractions of each filler. For the composites containing single fillers, the highest SE at 800 MHz were obtained for the 10 wt % highly branched CB/PC composite (18.9 dB) and the 8 wt % high aspect ratio CNT/ PC composite (18.4 dB). The platelet structure of the GNP produced composites with lower SE values. For the 15 wt % GNP/PC composite, the SE at 800 dB was 6.3 dB. Hence, filler structure plays an important role in composite SE.

Composites containing two different fillers were also fabricated and tested for SE. The highest SE of 21.4 dB was obtained at 800 MHz for the 5 wt % CB/5 wt % CNT/PC composite. In many cases, composites with $SE > 20$ dB could be used for shielding applications. Statistically significant equations were developed that could be used to predict the SE of composites containing these fillers. Per the authors' knowledge, for the first time in the open literature it was determined that the composite SE is higher than what would be expected from the additive effect of each single filler for the CB/GNP/PC composites. Adding highly branched CB to the platelet GNP structure creates additional pathways for EMI/RFI energy to be reflected and/or absorbed. Based on a literature review conducted by our research group, this is the first time in the open literature that the SE has been reported for this combination of carbon fillers (CB, CNT, and GNP) in polycarbonate.

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