Electrical and Thermal Conductivity and Tensile and Flexural Properties: Comparison of Carbon Black/Polycarbonate and Carbon Nanotube/Polycarbonate Resins

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ABSTRACT: Adding conductive carbon fillers to thermoplastic polymers increases the resulting composite's electrical conductivity. Carbon black (CB) is very effective at increasing composite electrical conductivity at low loading levels. In this study, varying amounts (2 to 10 wt %) CB were added to polycarbonate (PC) and the resulting composites were tested for electrical conductivity (1/electrical resistivity), thermal conductivity, and tensile and flexural properties. These results were compared with prior work done for carbon nanotubes (CNT) in polycarbonate. The percolation threshold was ∼ 2.3 vol % CB compared to between 0.7 and 1.4 vol % CNT. At 8 wt % filler, the CNT/PC composite had an electrical resistivity of 8 ohm-cm compared to 122 ohm-cm for the CB/PC composite. The addition of CB to polycarbonate increased the composite electrical and thermal conductivity and tensile and flexural modulus. The 8 wt % (5.5 vol %) CB in polycarbonate composite had a good combination of properties for semiconductive applications. Ductile tensile behavior is noted in pure polycarbonate and in samples containing up to 8 wt % CB. © 2011 Wiley Periodicals, Inc. J Appl Polym Sci 121: 2273–2281, 2011

INTRODUCTION

Most polymer resins are electrically insulating. Increasing the electrical conductivity (1/electrical resistivity, ER) of these resins allows them to be used in other applications, such as electrostatic dissipative (ESD, e.g., handling trays used in electronic equipment assembly, etc., ER typically 10^{10} to 10^3 ohm-cm) and moderately electrically conductive (e.g., fuel gauges, etc., ER typically 10^2 to 10^1 ohm-cm) applications. One approach to improving the electrical conductivity of a polymer is through the addition of a conductive filler material, such as carbon and metal.[1–14] Carbon black (CB) is a relatively inexpensive filler (∼ \$10/lb) that has been used to increase the electrical conductivity of a resin.[12,15–18] Recently, carbon nanotubes (CNTs) have been developed and explored for composite electrical conductivity applications.[19–23] CNTs are still more expensive (∼ \$100/lb) than carbon black.

In this work, researchers performed compounding runs followed by injection molding of carbon black filled polycarbonate (PC) resins. Composites containing varying amounts of carbon black were fabricated and tested for electrical and thermal conductivity, along with tensile and flexural properties. The first goal of this work was to determine the effects of carbon black on composite electrical conductivity, thermal conductivity, and tensile and flexural properties and to use this knowledge to identify composites with a good combination of properties for ESD and semiconductive applications. Adding more conductive filler does increase composite conductivity and also typically produces a less ductile (more brittle) composite. It is important to achieve the desired conductivity properties while still maintaining some ductile behavior. The second goal was to compare these results to previously published by the King research group for carbon nanotube/polycarbonate composites. Other researchers have used CB in PC[22–28]; however, the medium scale fabrication method (which is more suitable for scale up to commercial operations versus small scale typically reported in open literature) and higher electrical conductivity results obtained at lower CB concentrations make this contribution unique.

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MATERIALS AND EXPERIMENTAL METHODS

Materials

The matrix used for this project was Sabic's (Pittsfield, MA) Lexan HF1130-111 polycarbonate resin. The properties of this polymer are shown in Table I.[29]

The filler used in this study was Ketjenblack EC-600 JD. This is an electrically conductive carbon black available from Akzo Nobel, Inc. (Chicago, IL). The highly branched, high surface area carbon black structure allows it to contact a large amount of polymer, which results in improved electrical conductivity at low carbon black concentrations (often 5 to 7 wt %). The properties of Ketjenblack EC-600 JD are given in Table II.[18] The carbon black is sold in the form of pellets that are 100 μm to 2 mm in size and, upon mixing into a polymer, easily separates into primary aggregates 30 to 100 nm long.[18]

This article compares the results of this CB/PC work to that previously done by the King research group for CNT/PC composites. Hyperion Catalysis International's (Cambridge, MA) FIBRIL™ nanotubes were used in this prior study[30] and will be described here to assist the reader. This is a conductive, vapor grown, multiwalled carbon nanotube. They are produced from a high purity, low molecular weight hydrocarbons in a proprietary, continuous, gas phase, catalyzed reaction. The outside diameter of the tube is 10 nm and the length is 10 μm, which gives an aspect ratio (length/diameter) of 1000. Because of this high aspect ratio, very low concentrations of nanotubes are needed to produce an electrically conductive composite. This material was provided by Hyperion Catalysis International in a 15 wt % FIBRIL™ masterbatch MB6015-00. Table III shows the properties of the Hyperion Catalysis International FIBRIL™ multiwalled carbon nanotube.[19–21]

The concentrations (shown in wt % and the corresponding vol %) for all of the single filler composites tested in this research are shown in Table IV. We note that increasing filler amount increases composite melt viscosity. Table IV also shows the electrical resistivity and thermal conductivity results that will be described later in this paper. A composite containing 0.5 and 1 wt % CNT was fabricated only for conductivity testing.

TABLE I
Properties of Sabic's Polycarbonate Lexan HF 1130 (29)

Melt flow rate (300°C/1.2 kg)	25 g/10 min
Density	1.2 g/cc
Electrical resisitiviy	1×10^{17} ohm-cm
Thermal conductivity	0.19 W/m·K

TABLE II
Properties of Akzo Nobel Ketjenblack EC-600 JD (18)

Electrical resistivity	0.01–0.1 Ohm-cm
Aggregate size	30–100 nm
Specific gravity	1.8 g/cm³
Apparent bulk density	100–120 kg/m³
Ash vontent, max	0.1 wt %
Moisture, max.	0.5 wt %
BET surface area	1250 m²/g
Pore volume	480–510 cm³/100 g

Test specimen fabrication

Prior to extrusion and injection molding, the Lexan HF1130-111 was dried in an indirect heated dehumidifying drying oven at 121°C for 12 h. Ketjenblack EC-600 JD was used as received. The extruder used was an American Leistritz Extruder Corp. (Somerville, NJ) Model ZSE 27. This extruder has a 27 mm corotating intermeshing twin screw with 10 zones and a length/diameter ratio of 40. The melt temperature of the strands exiting the extruder was typically 290°C and the extruder was operated at 250 rpm at 4.5 kg/h and a specific energy of 0.8–1.0 kW/(kg/h). The screw design, which is shown in Figure 1, was chosen to obtain a minimum amount of filler degradation, while still dispersing the filler well in the polymers. A similar screw design was used successfully in the past to produce CB/polypropylene resins with good conductivity and mechanical properties.[31,32] The pure polycarbonate pellets were introduced in Zone 1. Ketjenblack EC-600 JD was introduced in Zone 5. This project uses a larger scale extruder, as compared to a 4.5 to 50 cm³ mechanical mixer, than is typically reported in the open literature.

After passing through the extruder, the polymer strands (3 mm in diameter) entered a water bath and then a pelletizer that produced nominally 3 mm long pellets. After extrusion, the polycarbonate based composites were dried in an indirect heated dehumidifying drying oven at 121°C for 12 h and then stored in moisture barrier bags prior to injection molding.

TABLE III
Properties of FIBRIL™ Carbon Nanotubes (19–21)

Composition	Pure carbon
Diameter	0.01 μm
Length	10 μm
Morphology	Graphitic sheets wrapped around a hollow 0.005 μm core
BET (N₂) surface area	250 m²/g
Density	2.0 g/cc of nanotube wall 1.75 g/cc for the hollow nanotube

TABLE IV
Single Filler Loading Levels in Polycarbonate and Electrical Resistivity and Thermal Conductivity Results

Formulation	Filler wt %	Filler vol %	Electrical resistivity (ohm-cm)	Thermal conductivity (W/m·K)
PC	0	0.0	$1.26 \times 10^{17} \pm 3.35 \times 10^{16}$ $n = 6$	0.214 ± 0.001 $n = 5$
2CB	2	1.34	$4.05 \times 10^{16} \pm 2.66 \times 10^{16}$ $n = 6$	0.228 ± 0.001 $n = 5$
3CB	3	2.01	$2.85 \times 10^{15} \pm 4.58 \times 10^{14}$ $n = 6$	0.234 ± 0.002 $n = 4$
4CB	4	2.69	$1.17 \times 10^{5} \pm 7.77 \times 10^{4}$ $n = 8$	0.245 ± 0.001 $n = 4$
5CB	5	3.38	2474 ± 646 $n = 8$	0.254 ± 0.001 $n = 4$
6CB	6	4.07	649 ± 18 $n = 8$	0.260 ± 0.001 $n = 4$
8CB	8	5.46	122 ± 4 $n = 8$	0.275 ± 0.003 $n = 4$
10CB	10	6.88	19.5 ± 0.5 $n = 8$	0.291 ± 0.003 $n = 4$
0.5CNT	0.5	0.34	$6.19 \times 10^{16} \pm 1.21 \times 10^{16}$ $n = 6$	0.218 ± 0.002 $n = 4$
1CNT	1	0.69	$2.02 \times 10^{16} \pm 6.62 \times 10^{15}$ $n = 6$	0.225 ± 0.005 $n = 4$
2CNT	2	1.38	4610 ± 1120 $n = 6$	0.232 ± 0.002 $n = 5$
3CNT	3	2.08	216 ± 44 $n = 6$	0.241 ± 0.003 $n = 5$
4CNT	4	2.78	73 ± 10 $n = 6$	0.255 ± 0.001 $n = 5$
5CNT	5	3.48	43 ± 7 $n = 6$	0.266 ± 0.003 $n = 5$
6CNT	6	4.19	18 ± 2 $n = 6$	0.275 ± 0.003 $n = 5$
8CNT	8	5.63	7.8 ± 0.4 $n = 6$	0.306 ± 0.003 $n = 5$

A Niigata (Tokyo, Japan) injection molding machine, model NE85UA$_4$, was used to produce test specimens. This machine has a 40 mm diameter single screw with a length/diameter ratio of 18. The lengths of the feed, compression, and metering sections of the single screw are 396 mm, 180 mm, and 144 mm, respectively. Typical injection molding temperatures were Zone 1 at 321°C (die end), Zone 2 at 299°C, Zone 3 at 290°C, and Zone 4 at 280°C (nearest feed hopper). A four cavity mold was used to produce 3.3 mm thick ASTM Type I tensile bars (end gated), 3.1 mm thick by 127 mm long by 12.7 mm wide flexural bars (end gated), and 3.4 mm thick with 6.4 cm diameter disks (end gated). This project uses a medium scale injection molding machine versus small scale compression molding that is often reported in open literature. Hence, the fabrication methods used in this project are more suitable for scale up to commercial operations.

Field emission scanning electron microscope and differential scanning calorimeter test methods

A JEOL Ltd. JSM-7500F (Tokyo, Japan) Field Emission Scanning Electron Microscope (FESEM) was used to view the surface of the CB/PC composite (3.2 mm thick by 12.7 mm wide cross section from an injection molded flexural bar). The sample was prepared for observation by mounting the composite in a cast epoxy puck. Then the surface was polished with SiC to a #4000 grit finish, followed by polishing
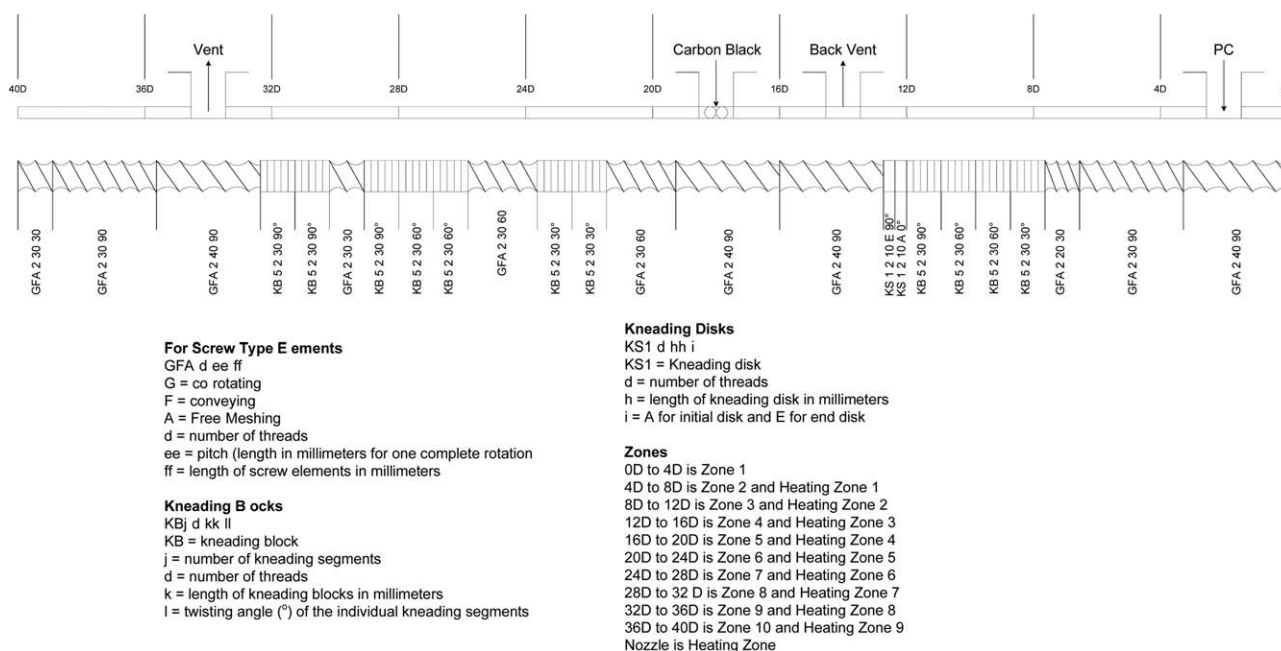
Figure 1 Twin screw extruder design.

with a 1 micron alumina/water slurry on a rotating lap cloth, and then finally with a 0.05 μm alumina/water slurry in a Buehler Vibromet (Lake Bluff, IL) polisher for 2 h. The composite surface was then etched in O_2 plasma at 23°C and 0.28 torr for 1 h and then sputter coated with approximately a 10 nm layer of gold. Finally, the samples were observed in the FESEM at 10 kV accelerating voltage, 6 mm working distance using the upper secondary electron detector. This method was used to view the CB in PC. These samples were prepared and micrographs taken by Huang Wu at the Composite Materials and Structures Center at Michigan State University.

A Mettler (Columbus, OH) model 823E DSC was used to measure T_g. Approximately 10 mg of each formulation was tested at 10°C/min ramp rate under a nitrogen gas purge.

Electrical resistivity test method

For samples with an electrical resistivity $>10^6$ ohm-cm, the volumetric electrical conductivity test was conducted. In this method, a constant voltage (100V) was applied to the as-molded test specimen, and the resistivity was measured according to ASTM D257 using a Keithley 6517A Electrometer/High Resistance Meter (Cleveland, OH) and an 8009 Resistivity Test Fixture.[33] The Keithley 6524 High Resistance Measurement Software was used to automate the conductivity measurement. Each test specimen was an injection molded disk that was 6.4 cm in diameter and 3.4 mm thick. Six samples were tested for each formulation. Prior to testing, the samples were conditioned at 23°C and 50% relative humidity for two days.

The in-plane volumetric electrical resistivity of the center 60 mm long, 3.3 mm thick, 12.7 mm wide tensile bars (rectangular necked area) injection molded tensile bars was determined according to ASTM D 4496 at 23°C for samples with an electrical resistivity $<10^6$ ohm-cm.[34] Prior to testing, the samples were conditioned at 23°C and 50% relative humidity for two days. Eight samples were tested for each formulation. This test was conducted with two probes. In the two probe method, the tensile bar was scratched with a razor blade, placed in liquid nitrogen, and then broken manually at the desired location. Hence, a fracture surface was created on both ends of the in-plane sample. Then the 3.3 mm thick by 12.7 mm wide ends were coated with silver paint and allowed to dry for 1 h. One probe was placed on each silver painted fracture surface and a constant voltage was placed across the sample using a Keithley 2400 Source Meter. The resulting current was also measured on this same Keithley 2400. The volume electrical resistivity is calculated from eq. (1) below:

$$ER = \frac{(\Delta V)(w)(t)}{(i)(L)} \qquad (1)$$

where ER = volume electrical resistivity (ohm-cm), ΔV = voltage drop over length of sample (volts), w = sample width (1.27 cm), t = sample thickness (0.33 cm), i = current (amps), and L = length over which ΔV is measured (6 cm).

Thermal conductivity test method

The through-plane thermal conductivity of a 3.4 mm thick, 5 cm diameter disk shaped test specimen was measured at 55°C using a Holometrix (Burlington, MA) Model TCA-300 Thermal Conductivity Analyzer, which uses the ASTM F433 guarded heat flow meter method.[35] For each formulation, at least four samples were tested. Prior to testing, the samples were conditioned at 23°C and 50% relative humidity for two days.

Tensile test method

The tensile properties (at ambient conditions, 165 mm long, 3.3 mm thick ASTM Type I sample geometry) from all formulations were determined using ASTM D638 at a crosshead rate of 5 mm/min for reinforced plastics.[36] An Instru-Met Sintech (Union, NJ) screw driven mechanical testing machine was used. Tensile modulus was calculated from the initial linear portion of the stress-strain curve. For each formulation, at least five samples were tested. Prior to testing, the samples were conditioned at 23°C and 50% relative humidity for two days.

Flexural test method

The flexural properties (at ambient conditions, 3.1 mm thick by 127 mm long by 12.7 mm wide flexural bars) were determined using three-point loading at ambient conditions from all formulations according to ASTM D790[37] at a crosshead rate of 5.3 mm/min. A 16 : 1 span to thickness ratio was used in an Instru-Met Sintech screw driven mechanical testing machine. Deflection was measured using a LVDT (linear variable displacement transducer). Flexural modulus was calculated from the initial linear portion of the stress-strain curve. For each formulation, at least eight samples were tested. Prior to testing, the samples were conditioned at 23°C and 50% relative humidity for two days.

RESULTS

FESEM and DSC results

Figure 2 shows the CB (white spheres) in the sample containing 6 wt % CB. As expected, a nanosize
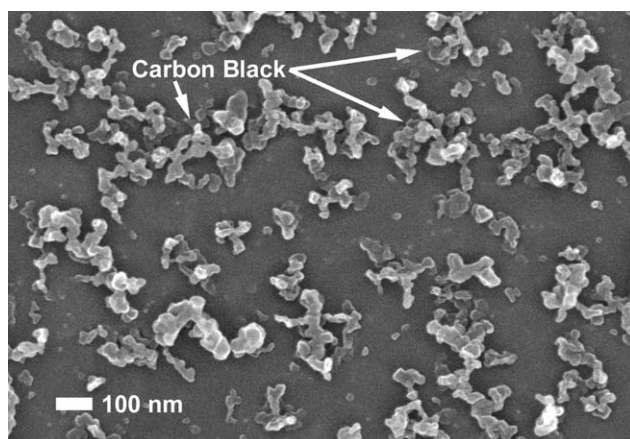
Figure 2 FESEM micrograph of 6 wt % carbon black/ polycarbonate composite.

highly structured carbon black is seen and numerous conductive paths are present due to the close proximity of the carbon black to each other.[12] The T_g values remained constant at ~ 144°C for all formulations. Apparently, CB is not significantly affecting polymer chain mobility. Micrographs showing the dispersion of CNT in PC have been reported previously by our research group.[30]
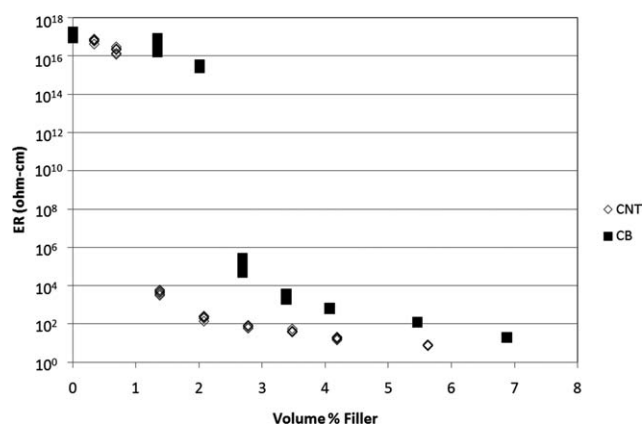
Electrical resistivity results

The mean, standard deviation, and number of samples test for each formulation containing varying amounts of single fillers are shown in Table IV. Figure 3 shows the log (electrical resistivity in ohm-cm) for composites containing varying amounts of CB as a function of filler volume fraction. In this figure, all the data points have been plotted. Figure 3 follows the typical electrical resistivity curve. At low filler loadings, the electrical resistivity remains similar to that of the pure polymer. Then at a point called the percolation threshold, the resistivity decreases dramatically over a very narrow range of filler concentrations. At higher filler loadings, the electrical resistivity begins to level out again at a value many orders of magnitude lower than that of the pure polymer.[5,38]

Figure 3 illustrates that carbon black is effective at decreasing the electrical resistivity (1/electrical conductivity) at low filler loadings. The pure polycarbonate has a mean electrical resistivity of 1.3×10^{17} ohm-cm, which agrees with the vendor literature value (see Table I). The percolation threshold occurs at ~ 2.3 vol % for carbon black. At the highest filler concentration, the carbon black produced a mean composite resistivity of 20 ohm-cm (10 wt % = 6.9 vol %). It is interesting to compare work previously done by the King research group for Hyperion Catalysis International's (Cambridge, MA) FIBRIL™

multiwalled carbon nanotubes (CNT) in the same polycarbonate.[30] These values are also shown on Figure 3. The percolation threshold for the CNT/PC composites is between 0.7 and 1.4 vol % (1 to 2 wt %) CNT. At the highest filler concentration, the carbon nanotubes produced a mean composite resistivity of 8 ohm-cm (8 wt % = 5.6 vol %). The lower percolation threshold for the CNT/PC composites is likely due to the extremely high aspect ratio (length/diameter) of 1000 for CNT. This same high aspect ratio for CNT also likely increases the electrical conductivity (1/electrical resistivity) as compared with similar concentrations of CB. For example, for 8 wt % (5.6 vol %) CNT, the electrical resistivity was 8 ohm-cm as compared with 122 ohm-cm for 8 wt % (5.5 vol %) CB.

Several other researchers have used CB in PC.[22–27] For similar concentrations, our CB/PC composites are more conductive than those reported by Tchoudakov et al., Ezquerra et al., Calleja et al., Narkis et al., Lee et al., and Potschke et al. for carbon black in polycarbonate.[22–27] In addition, our fabrication methods use larger scale equipment which is easier to scale up to commercial operations. Five of these papers use compression molding as opposed to the injection molding that was used in this current study. Injection molding is typically a more cost effective and commercially viable fabrication method. These papers will be described here in more detail. Potschke et al. investigated using Cabot Corp. Vulcan XC72 electrically conductive carbon black in Mitsubishi Engineering Plastics polycarbonate. These researchers used a small scale conical corotating twin screw extruder with a capacity of 4.5 cm^3 and compression molded 0.35 mm thick plates for testing.[23] They obtained an ER of ~ 10^8 ohm-cm for composite containing 10 wt % CB as opposed to our ER value of 20 ohm-cm for the same concentration of CB. Lee et al. investigated using Korea

Figure 3 Electrical resistivity results for carbon black/ polycarbonate and carbon nanotube/polycarbonate composites.
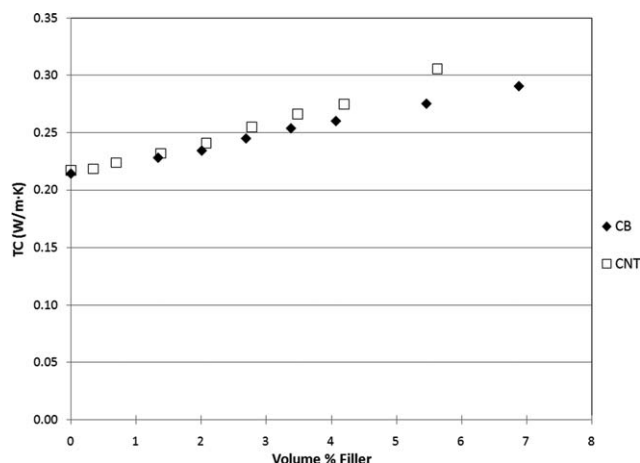
Figure 4 Thermal conductivity results for carbon black/polycarbonate and carbon nanotube/polycarbonate composites.

Carbon Black Co. Hiblack 30 electrically conductive carbon black in SAMYANG Co. TRIREX 3022 polycarbonate. These researchers compounded and compression molded 25 mm diameter disks that were 1.5 mm thick for testing.[22] At 10 wt % CB, Lee et al. reported an ER ~ 10^{15} ohm-cm compared with our ER value of 20 ohm-cm for the same concentration of CB. Balta Calleja et al.[26] used a Bayer polycarbonate and a CB from SEA Tutor. They obtained an ER value of ~ 10^{15} ohm-cm for ≤9 vol % CB. The ER values presented in this current article are lower than those obtained by Balta Calleja et al. Ezquerra et al.[25] used Philips Petroleum XE2 electrically conductive CB in a Bayer polycarbonate. The material was mechanically stirred at 50 rpm in a small scale mixer for then 10 min and then compression molded into test specimens. They obtained an ER value of ~ 10^4 ohm-cm for a composite containing 6.4 vol % CB, as opposed to the ER value of 20 ohm-cm we obtained for 6.9 vol % CB. Tchoudakov et al.[24] combined GE Plastics Lexan 103 polycarbonate with Akzo Ketjenblack EC carbon black in a small scale mixer (50 cm³ cell) and compression molded test specimens. At 8 wt % CB, Tchoudakov et al. reported 10^7 ohm-cm as opposed to our value of 122 ohm-cm. Narkis et al.[27] used Ketjenblack EC-600 JD, the same carbon black that is used in this current study, in a Lexan polycarbonate (exact one used is not given). The material was compounded in a twin screw extruder and injection molded into specimens. Narkis et al. obtained an ER ~ 10^8 ohm-cm for 6 wt % CB as compared to our ER value of 650 ohm-cm for the same concentration of carbon black.

Thermal conductivity results

Figure 4 shows the mean through-plane thermal conductivity using the guarded heat flow meter for the composites containing only varying amounts of single fillers as a function of filler volume fraction. These formulations correspond to those shown in Table IV.

Figure 4 shows that carbon black does increase the through-plane thermal conductivity of the polymer from 0.21 W/m·K to 0.29 W/m·K for the composites containing 10 wt % (6.9 vol %) CB. Once again, for comparison reasons, prior work conducted by our research group is also shown for Hyperion Catalysis International's (Cambridge, MA) FIBRIL™ multi-walled carbon nanotubes (CNT) in the same polycarbonate.[30] At similar filler concentrations, the composite thermal conductivity is slightly higher for the CNT/PC composites. These values are similar to those previously reported by the King research group for Ketjenblack EC-600 JD in polypropylene[39] and in Vectra A950RX liquid crystal polymer.[40] The authors did not find thermal conductivity values of CB/PC composites presented by others in the open literature.

Tensile test results

Figures 5 and 6 show the tensile results (tensile modulus, ultimate tensile strength, and strain at ultimate tensile strength) mean and ± one standard deviation for composites containing varying amounts of single fillers as function of volume percent filler. These formulations correspond to those shown in Table IV. If the standard deviation is smaller than the marker size, the error bars are not shown. The tensile modulus results are located in Figure 5. Adding CB caused the tensile modulus to increase from 2.2 GPa (neat polymer) to 2.8 GPa at 8 wt % (5.5 vol %) CB and 3.0 GPa at 10 wt % (6.9 vol %) CB. Figure 5 also shows the CNT/PC results from prior work by our research group.[30] Adding CNT caused the tensile modulus to increase from 2.2
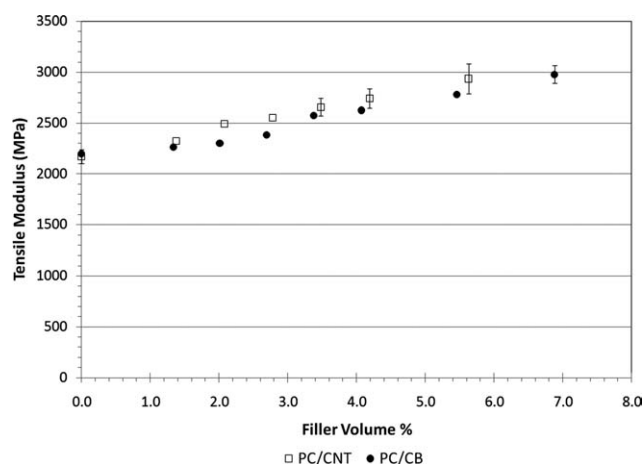
Figure 5 Tensile modulus for carbon black/polycarbonate and carbon nanotube/polycarbonate composites.
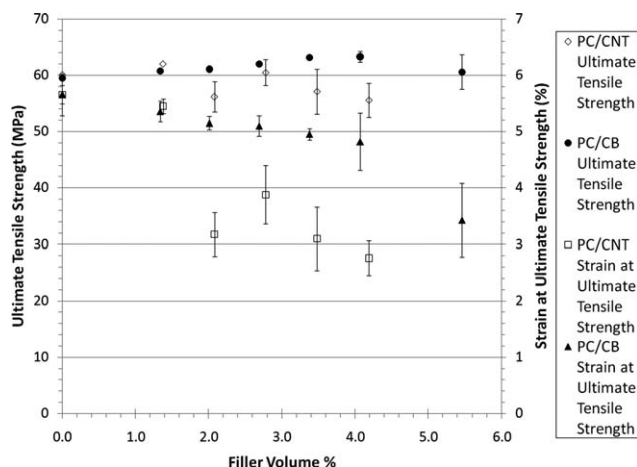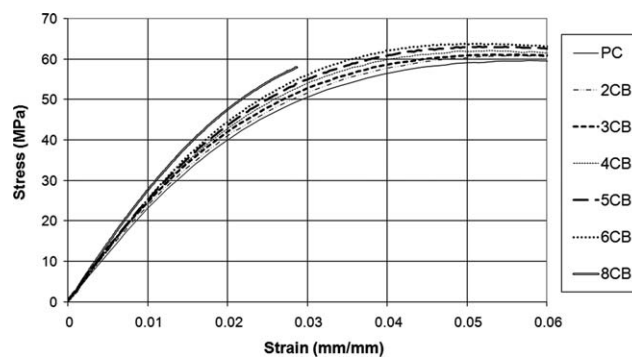
Figure 6 Ultimate tensile strength and strain at ultimate tensile strength for carbon black/polycarbonate and carbon nanotube/polycarbonate composites.

GPa (neat polymer) to 2.9 GPa at 8 wt % (5.6 vol %) CNT. At similar filler concentrations, the tensile modulus values are similar for CB and CNT in the same polycarbonate.

Figure 6 illustrates the ultimate tensile strength (UTS) and strain at UTS results. The results for the 10 wt % (6.9 vol %) CB in polycarbonate composite are not shown since the sample broke prematurely (the resin was very viscous and was difficult to injection mold at this highest filler content). Figure 6 shows that the UTS is similar (ranging from 60 to 63 MPa) for all the composites containing ≤ 8 wt % (5.5 vol %) CB. This figure also shows that the strain at UTS generally decreases with the addition of CB. Figure 6 also shows the CNT/PC results from prior work by our research group.[30] For the CNT/PC composites, the UTS remains relatively constant at about 60 MPa and the strain at UTS generally decreases as CNT concentration increases. Apparently, the high structure and high surface area carbon black is able to form networks (see Fig. 2) that produce tensile properties similar to CNT/PC composites. It is interesting to note that for our work, the CB/PC composites do have a higher strain at UTS as compared to the CNT/PC composites.

Similar tensile property trends were found by Huang et al. for carbon black in polycarbonate.[28] Huang et al.[28] used Cabot Corp. electrically conductive carbon black Vulcan XR 72R and Miles Inc. Makrolon 2608 polycarbonate. To fabricate the materials, they used a 19 mm single screw extruder and a 20 ton injection molding machine to produce specimens. They reported an increase in tensile strength from 59.3 MPa (neat PC) to 63.4 MPa for 5 wt % CB in PC. These tensile strength results are very similar to the ones reported in this current paper. Huang et al. also reported a 10% increase in tensile modulus as compared to the neat PC for 5 wt % CB in

PC, which is also similar to that seen in Figure 5 for 5 wt % CB in PC. Hence, the larger scale extruder and injection molding machine used in this current project produced similar tensile property trends.

Figure 7 shows a typical tensile stress-strain curve (up to 6% strain) for polycarbonate and for composites containing up to 8 wt % CB in polycarbonate. This figure shows that in all cases, ductile behavior of the neat polymer is retained after the addition of carbon black.


Figure 7 Tensile stress-strain curves for polycarbonate and carbon black/polycarbonate composites.

Flexural test results

Figures 8 and 9 show the flexural modulus, ultimate flexural strength, and strain at ultimate flexural strength (mean and ± one standard deviation) for composites containing varying amounts of single fillers as function of filler volume percent. These formulations correspond to those shown in Table IV. If the standard deviation is smaller than the marker size, the error bars are not shown.

Figure 8 shows the flexural modulus for composites containing varying amounts of single fillers. Figures 5 (tensile modulus) and 8 (flexural modulus)
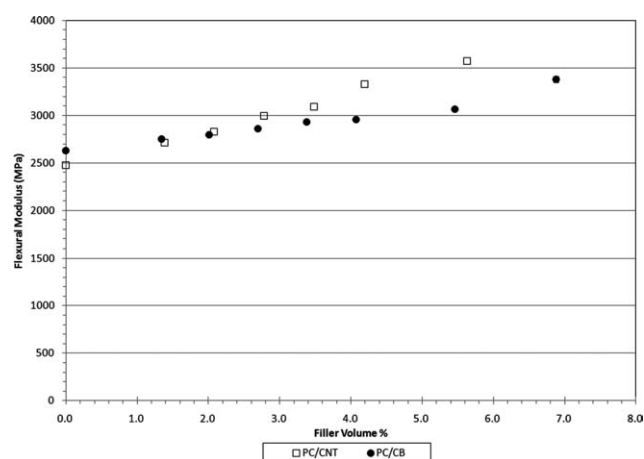
Figure 8 Flexural modulus for carbon black/polycarabonate and carbon nanotube/polycarbonate composites.
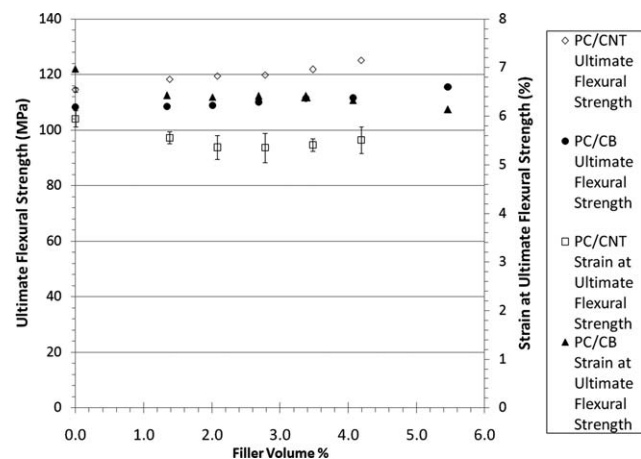
Figure 9 Ultimate flexural strength and strain at ultimate flexural strength for carbon black/polycarbonate and carbon nanotube/polycarbonate composites.

show the same general trends. Adding CB caused the flexural modulus to increase from 2.6 GPa (neat polymer) to 3.4 GPa at 10 wt % (6.9 vol %) CB. Figure 8 also shows the CNT/PC results from prior work by our research group.[30] Adding CNT caused the flexural modulus to increase from 2.6 GPa (neat polymer) to 3.6 GPa at 8 wt % (5.6 vol %) CNT.

Figure 9 shows the ultimate flexural strength and strain at ultimate flexural strength. Once again, the results for the 10 wt % CB in polycarbonate composite are not shown since the sample broke prematurely. The addition of CB caused an increase in ultimate flexural strength from 108 MPa for the neat polymer to 116 MPa with 8 wt % (5.5 vol %) CB. The strain at ultimate flexural strength remained approximately the same at 6.1% to 6.4% for all CB concentrations. Figure 9 also shows the CNT/PC results from prior work by our research group.[30] The addition of CNT caused an increase in ultimate flexural strength from 115 MPa for the neat polymer to 125 MPa with 6 wt % (4.2 vol %) CNT. For the CNT/PC composites, the strain at ultimate flexural strength remained approximately the same at 5.4% to 5.6% for all loading levels. Again it appears that the high structure and high surface area carbon black is able to form networks that produce flexural properties similar to CNT/PC composites. In agreement with our tensile results, higher strain at ultimate flexural strength is noted for our CB/PC composites as compared to our CNT/PC composites. Similar flexural modulus trends have been noted by Huang et al. for carbon black in polycarbonate.[28] For example, Huang reported an increase in the flexural modulus from 1676 MPa (neat PC) to 2117 MPa for 5 wt % CB in PC. This current project shows a similar trend for 5 wt % CB in PC (see Fig. 8).

CONCLUSIONS

The object of this research was to determine the effects of carbon black on the composite properties, to compare these results with those of CNT in the same polycarbonate, and to identify CB/PC composites with a good combination of properties for ESD and semiconductive applications. Concerning electrical properties, the percolation threshold is approximately 2.3 vol % CB. Adding CB decreased the electrical resistivity from 1.3×10^{17} ohm-cm (neat polymer) to 20 ohm-cm for the composite containing 10 wt % (6.9 vol %) CB. Because of the extremely high aspect ratio (length/diameter) of 1000 for CNT, the CNT/PC composites are more electrically conductive. For example, the percolation threshold for the CNT/PC composites is between 0.7 and 1.4 vol % (1 to 2 wt %) CNT and the 8 wt % (5.6 vol %) CNT in PC composite had a mean composite resistivity of 8 ohm-cm. For similar concentrations, the CB/PC composites reported in this work are more electrically conductive than those reported by others for CB/PC composites.[22–27] Another unique feature of this study is the medium scale fabrication methods used which are more suitable for scale up to commercial operations.

CB is a relatively inexpensive conductive filler at ~ \$10/lb as compared to ~ \$100/lb for CNT. The composite with 8 wt % (5.5 vol %) CB in polycarbonate had a good combination of properties for semiconductive applications. The electrical resistivity and thermal conductivity were 122 ohm-cm and 0.28 W/m·K, respectively. The tensile modulus, ultimate tensile strength, and strain at ultimate tensile strength were 2.8 GPa, 61 MPa, and 3.4%, respectively. The flexural modulus, ultimate flexural strength, and strain at ultimate flexural strength were 3.1 GPa, 116 MPa, and 6.1%, respectively. For semiconductive applications, this composite could be used instead of 4 wt % CNT in polycarbonate. The composite with 4 or 5 wt % CB in polycarbonate could be suitable for ESD applications and could be used in place of one containing 2 wt % CNT in polycarbonate.

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