Mechanical and electrical properties of epoxy resin/ epoxidized castor oil/carbon fiber cloth composites

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Carbon fibers (CFs) have a unique combination of outstanding mechanical, physical, and chemical properties and are among the materials most frequently used in the preparation of a large variety of composites [1-5]. CF-reinforced polymer composites have been widely used in many advanced technological fields, such as aerospace, engineering, sporting goods, automobiles, and marine industry during the past few decades due to their excellent properties, including high strength-to-weight ratios, light weight, high thermal and electrical conductivity, and relative ease of processing [6-10].

However, CFs have poor wettability and adsorption when used with most polymer matrices to make CF-reinforced composites because pristine CFs have chemically inert surfaces and low surface energy. Thus, the properties of the composites are determined not only by the CFs and the polymer matrix, but also by the interface and interphase formed between the two constituents. In general, interfacial adhesion is dominated by the surface properties of CFs (roughness, porosity, functional groups) and the chemical character of the matrix. Favorable interfacial adhesion can efficiently transfer stress from the matrix to the CFs. This plays a major role in determining the mechanical performance and reliability of the composites [11-14].

Various surface modification techniques have been developed to increase the number of surface functional groups and thus enhance the interactions and/or adhesion between the CFs and the matrix. Different surface treatment methods have been used: gas-phase, wet chemical, or electrochemical oxidation, ozone treatment, polymer coating (sizing), and plasma treatment [15-17]. These treatments of CFs improve the interfacial bonding of the final composites to some extent, but unfortunately require high energy consumption. Moreover, during the manufacturing process, commercial CFs are always coated with a sizing layer (epoxy resin) after surface chemical treatment. The epoxy coatings on the surfaces of the CFs are often not removed during the fabrication of CF-reinforced polymer composites. The sizing agents can alter the surface properties of the CFs, as well as their wettability and chemical reactions with the polymer matrix [18-20]. The epoxy matrix in the composite provides bulk and enables the transfer of loads between fibers. The diglycidylether of bisphenol A (DGEBA) is the most commonly used epoxy resin. However, the DGEBA matrix is relatively brittle and has little tensile strength. Therefore, many epoxy resin formulations need to be toughened [21,22].

Thermally latent initiators are inert under normal conditions, i.e., at ambient temperature and light, and become active only under external stimulation such as heating or photoirradiation. Therefore, a thermally latent initiator can easily control the initiation and curing process of an epoxy system, which is desirable for the enhancement of both pot life and handling of epoxy resins [23-26].

In this study, we prepared CF-reinforced epoxy composites using DGEBA as a matrix, epoxidized castor oil (ECO) as a reactive diluent, and carbon fiber cloth (CFC) as a reinforcing agent. We investigated mechanical and electrical properties of the DGEBA/ECO/CFC composites using a universal testing machine, an Izod impact tester, and a direct current (DC) resistance tester.

The epoxy resin used in this study was DGEBA (E-51) supplied by Feicheng Deyuan Chemical Co., Ltd. of China, which had an epoxide equivalent weight (EEW) of 185–208 g/

eq. ECO was synthesized in our lab [23,25,27]. CFC (K12) was purchased from Jilin Jiyan High-Tech Fibers Co., Ltd., (China) and was sized with epoxy resin. The thermally latent initiator *N*-benzylpyrazinium hexafluoroantimonate (BPH) was synthesized as in our previous work [24]. Hydroxyl multi-wall carbon nanotubes (CNTs) (MH5 111216) were supplied by the Chengdu Organic Chemicals Co., Ltd. of the Chinese Academy of Sciences and had diameters of 20–30 nm, lengths of 10–30 m, and OH content of 1.76 wt%.

The ECO was synthesized as follows: castor oil (30 g), glacial acetic acid (4.5 g), and phosphoric acid (0.3 g) were loaded into in a round, four-necked 250 mL flask equipped with a mechanical stirrer, thermocouple, and reflux condenser. The mixture was heated to a constant temperature of 70°C. Then, 30% H_2O_2 (24 g) was slowly added to the flask and allowed to react at 70°C for 4 h. After the reaction was complete, the crude product was filtered and washed with a distilled water and then distilled in a vacuum oven at 70°C for 1 h (yield 81%; EEW 510–520 g/eq; Mn 1411 g/mol; Mw 1518 g/mol; hydroxyl number per molecule, 2.8).

The BPH was synthesized as follows: a solution of pyrazine (2.4 g) in acetonitrile (15 mL) was added to benzyl bromide (6.16 g) and the mixture was stirred and allowed to react at room temperature for 4 days. The precipitated solid was collected by filtration and washed with benzene. The solid product was dried in a vacuum and added to a solution of $NaSbF_6$ in H_2O (25 g). The mixture was then stirred for 30 min. The anion exchange product was filtered and washed with ether and then dried in a vacuum. The resulting product was re-crystallized from methanol, and white crystals were obtained (yield 73%).

Non-sized CFCs were prepared as follows: to remove the sizing agent from CFC surfaces, the CFCs were heated in acetone solvent at 75°C for 10 h.
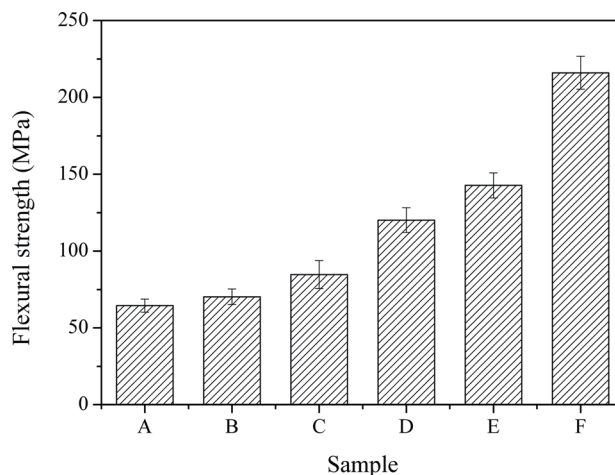
The DGEBA/ECO/CFC composites were prepared as shown in Table 1. The designated amounts of DGEBA and ECO were mixed and heated in an oil bath at 80°C for 30 min, after which 1wt% BPH was added. The mixture was stirred and degassed in a vacuum oven. The mixture was injected into a preheated mold in which a specific amount of CFC had been placed. The mold was compression-cured at temperatures ranging from 120 to 180°C and a pressure of 4 MPa. The specimens were cut to suitable dimensions for mechanical tests.

The flexural tests were performed using a universal testing
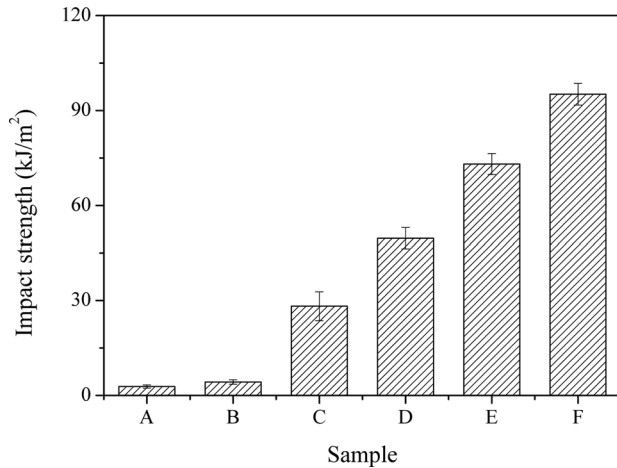

Fig. 1. Flexural strength of DGEBA/ECO/CFC composites as a function of the amount of CFC. DGEBA, diglycidylether of bisphenol A; ECO, epoxidized castor oil; CFC, carbon fiber cloth; CNTs, carbon nanotubes.
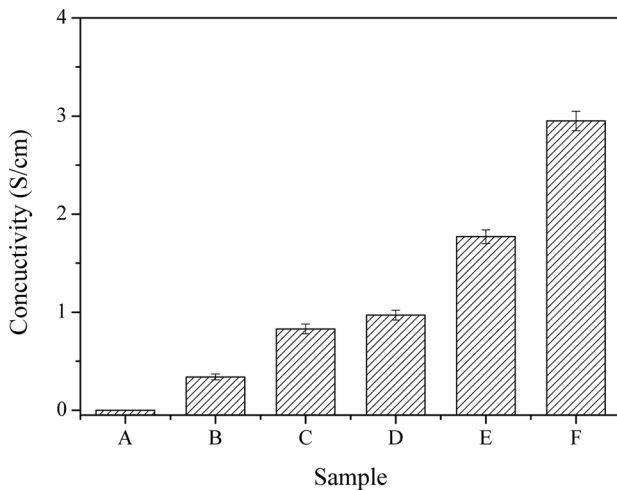
machine (Instron Model WDW3010, Korea) according to GB/T 9341-2000 with a three-point bend configuration. The sample size was 5×10×100 mm³. Impact strength tests were performed using an Izod impact tester pursuant to GB/T 1843-2008. The specimen size was 4×10×80 mm³. The resistivity was measured at room temperature using a DC resistance tester (AST10A) pursuant to GB/T 24525-2009. The sample size was 5×50×50 mm³.

The DGEBA/ECO/CFC composites were prepared via a hot melt lay-up plus a compression-curing process, and their mechanical and electrical properties were investigated. Fig. 1 shows the flexural strength of the DGEBA/ECO/CFC composites as a function of the amount of CFC incorporated. The flexural strength increased slightly from 64.4 to 70.4 MPa when 2 layers of non-sized CFC were used. This was due to poor wettability between the CFCs and the epoxy matrix. In contrast, the flexural strength increased from 64.4 to 84.6 MPa as the amount of CFC increased from 0 to 2 layers, and further increased from 84.6 to 142.7 MPa as the amount of CFC increased from 2 to 4 layers. The flexural strength further increased from 142.7 to 216 MPa when the amount of CFC was increased from 4 to 5 layers. These results can be explained as follows: epoxy sizing confers on the CFC an equivalent electron donor and acceptor character, which enhances the wettability of the CFCs by DGEBA, resulting in improved interfacial adhesion between the CFCs and the epoxy matrix [28,29].

Fig. 2 presents the impact strength of the DGEBA/ECO/CFC composites as a function of CFC amount. As shown in Fig. 2, the neat DGEBA was very brittle, exhibiting an impact strength of 2.8 kJ/m². The impact strength increased slightly from 2.8 to 4.2 MPa when 2 layers of non-sized CFC were used. In contrast, the impact strengths of the composites containing 2, 3, 4, and 5 layers of CFC were 8.9 times higher at 28.2 kJ/m², 16.4 times higher at 49.6 kJ/m², 24.6 times higher at 73.0 kJ/m², and 32.3 times higher at 95.1 kJ/m², respectively. When the composites are under load, their strong interface can effectively transfer load from the matrix to the CFC, which can efficiently absorb the fracture energy, resulting in increases in the impact strengths

Table 1. Preparation conditions of DGEBA/ECO/CFC composites

Sample	DGEBA (wt%)	ECO (wt%)	CFC	CFC amount (layer)
A	80	20	-	0
B	80	20	Non-sized CFC	2
C	80	20	Sized CFC	2
D	80	20	Sized CFC	3
E	80	20	Sized CFC	4
F	80	20	Sized CFC	5

DGEBA, diglycidylether of bisphenol A; ECO, epoxidized castor oil; CFC, carbon fiber cloth.

Fig. 2. Impact strength of DGEBA/ECO/CFC composites as a function of the amount of CFC. DGEBA, diglycidylether of bisphenol A; ECO, epoxidized castor oil; CFC, carbon fiber cloth; CNTs, carbon nanotubes.

Fig. 3. Conductivity of DGEBA/ECO/CFC composites as a function of the amount of CFC. DGEBA, diglycidylether of bisphenol A; ECO, epoxidized castor oil; CFC, carbon fiber cloth; CNTs, carbon nanotubes.

Table 2. Mechanical and electrical properties of DGEBA/ECO/CFC composites before and after addition of CNTs (4 layers of CFC)

CNTs (wt%)	Flexural strength (MPa)	Impact strength (kJ/m^2)	Conductivity (S/cm)
0	142.7±2.2	73.1±3.3	1.77±0.07
0.5	153.5±2.4	74.7±3.4	2.38±0.08

Values are presented as mean±standard deviation.
DGEBA, diglycidylether of bisphenol A; ECO, epoxidized castor oil; CFC, carbon fiber cloth; CNTs, carbon nanotubes.

The conductivity of a DGEBA/ECO/CFC composite containing 4 layers of CFC and 0.5 wt% CNTs was 2.38 S/cm, which was 34% higher than that of DGEBA/ECO/CFC composite containing 4 layers of CFC. This was due to the high electrical conductivity of CNTs (10^4 S/cm). These results indicate that the electrical conductivity was significantly enhanced by the addition of a small amount of CNTs (0.5 wt%) to the DGEBA/ECO/CFC composites [35,36].

In summary, the DGEBA/ECO/CFC composites were prepared and their mechanical and electrical properties were investigated using several techniques. The flexural strength and impact strength of the composites were slightly increased by the addition of non-sized CFCs. The flexural strength and impact strength of the composites increased significantly with the amount of CFC included. When 5 layers of CFC were used, the flexural strength and impact strength of the composite were 2.3 and 32.3 times higher, respectively, than those of neat DGEBA. The electrical conductivity of the composites increased with the addition of CFC. The addition of a small amount of CNTs (0.5 wt%) to the DGEBA/ECO/CFC composites significantly enhanced their electrical conductivities without affecting their mechanical properties.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgements

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of the DGEBA/ECO/CFC composites [30-32].

Fig. 3 shows the electrical conductivities of DGEBA/ECO/CFC composites as a function of the amount of CFC included. The conductivity increased slightly from 0 to 0.34 S/cm when 2 layers of non-sized CFC were used. In contrast, the conductivity increased from 0 to 0.97 S/cm as the amount of CFC increased from 0 to 3 layers and then further increased from 0.97 to 2.95 S/cm when the amount of CFC was increased from 3 to 5 layers. These results can be attributed to the high electrical conductivity of CFs (10^3 S/cm) [33].

We investigated the effects of the use of CNTs as conductive fillers on the mechanical and electrical properties of DGEBA/ECO/CFC composites, and the results are shown in Table 2. The flexural and impact strengths of the composite increased slightly with the addition of CNTs. The results indicate that the fiber–matrix interface was not weakened by the addition of CNTs [14,18,34].

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