STUDY ON THE ELECTROMAGNETIC INTERFERENCE OF CARBON FIBER/CEMENT COMPOSITES BY REFLECTIVITY

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Abstract

The electromagnetic interference (EMI) of carbon-fiber-reinforced cement-based composites (carbon fiber/cement composites, CFRC) was traditionally assessed by measuring their shielding effectiveness (SE) directly using the Hewlett Packard 8752C set-up. However, EMI can also be evaluated indirectly by reflectivity using the Naval Research Laboratory (NRL) testing system. In this work, carbon fibers were dispersed uniformly in the cement matrix and the influence of their dispersion on the mechanical properties was discussed. The microstructure of the fracture surface of the CFRC samples was observed in a scanning electronic microscope (SEM). The reflectivity of the electromagnetic radiation by the composites was measured in the frequency range of 8.0~18.2 GHz for different carbon fiber contents of 0.2 %, 0.4 %, 0.6 %, 0.8 %, and 1.0 wt%. Results showed that the reflectivity decreased with the increasing of fiber contents till the percentage of 0.6 %. The minimum reflectivity was -23dB, far less than -10 dB, and the composites were strong wave absorbers. After this percentage, the reflectivity rose abruptly as the content proceeded. The electromagnetic waves were gradually reflected. When the fiber content reached 1.0 % finally, the reflectivity read -7.5dB and there was strongest reflection.

Keywords: Carbon fibres; Carbon composites; Adsorption; Electrochemical properties

Introduction

Electromagnetic interference (EMI) refers to electric or magnetic noises, which might emit from computers, calculators, automobile communication systems, televisions, mobile telephones, and other electronic products. The electromagnetic waves may result in faulty actions or malfunction of electronic products and lead to radioactive damage of human bodies. Therefore, EMI shielding problems are now receiving more and more attention from the scientific circles. The common way to avoid EMI problems is to use the materials with high conductivity, such as metals or conductive fibers as a shielding package [1– 4]. Typical metals such as copper and aluminum have been used for EMI shielding materials owing to their high conductivity and dielectric constant [2, 3]. However, there is an increasing interest in the use of carbon-fiber- reinforced cement-based composites (CFRC) in the fields of EMI shielding. Compared with metals, a conductive carbon fiber has the advantages with regard to low density, high modulus, high strength, variety in shape design, better appearance, light weight and low cost. Since carbon fiber is finding an increasing application in making various composites with special properties, the new CFRC has been developed which has the highest potential for both enhancing mechanical properties and providing EMI shielding against some radiation.

Cement composites are usually poor conductivity materials. Carbon fiber, however, exhibits good electricity conductivity with low resistivity ($(8\sim9)\times10^{-3}\ \Omega cm$) except for its high elasticity and

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resistance to corrosion. CFRC is a newly developed functional material due to its electrical conductivity characteristics. Continuous conductive current can be formed inside carbon fibers in CFRC upon the action of electromagnetic waves. The electrical conductivity of carbon fibers means that the addition of short fibers into cement significantly increases the ability of the composites to reflect microwaves, thus allowing EMI shielding and lateral guidance in automatic highways [4, 5].

The EMI shielding mechanism includes mainly reflection, absorption and multiple reflections, but the primary mechanism is usually reflection. A shielding material must reflect or/and absorb electromagnetic waves effectively [5, 6]. Carbon fibers usually reflect microwaves except that those after special treatment absorb microwaves. In other words，reflection is usually the dominant mechanism, especially for carbon fibers. The contribution by multiple reflections is usually relatively small for carbon composites. Although reflectivity is not a direct criterion for evaluating EMI shielding, it can reflect the shielding effectiveness indirectly. Therefore, this research is focused on the reflection properties of CFRC, through which the EMI shielding is revealed.

Experimental

Materials

The carbon fibers used were PAN-based 5 mm in length provided by *Jiyan* Carbon Ltd., Co. (*Jilin*, China). Their mass fraction was 0.2 %, 0.4 %, 0.6 %, 0.8 %, and 1.0 %, respectively, by weight of cement. The major parameters are listed in Table 1. The matrix was 32.5 R Portland cement (*Yaoxian* Cement Plant, *Shaanxi*, China). The dispersants used were hydroxyethyl cellulose (HEC) made in *Shandong* with the viscosity of 30000 Pa.S and silicon fume (300 mesh, purity 99.7 %, *Shanghai*). The mass fraction of HEC was in the amount of 0.6 %. Silicon fume was used in the amount of 10 %. A water-reducing agent naphthalenesulfonate formal condensate (FDN) was used in the amount of 0.5 %. The liquid defoamer tributyl phosphate (TBP) (*Tianjin* Chemical Reagent Plant, China) was added in 0.05 %. All the admixtures were used by weight of cement. Sand used was China ISO Standard (*Xiamen* Standard Sand Co., Ltd, China).

Table 1. Major parameters of short carbon fibers

Diameter / um	**Density / g/cm^3**	**Tensile strength / GPa**	**Shear strength / MPa**	**Modulus / GPa**	**Resistivity / Ωcm**
7±0.2	1.76－1.78	2.5－3.0	80	200－220	310

Preparation of CFRC samples

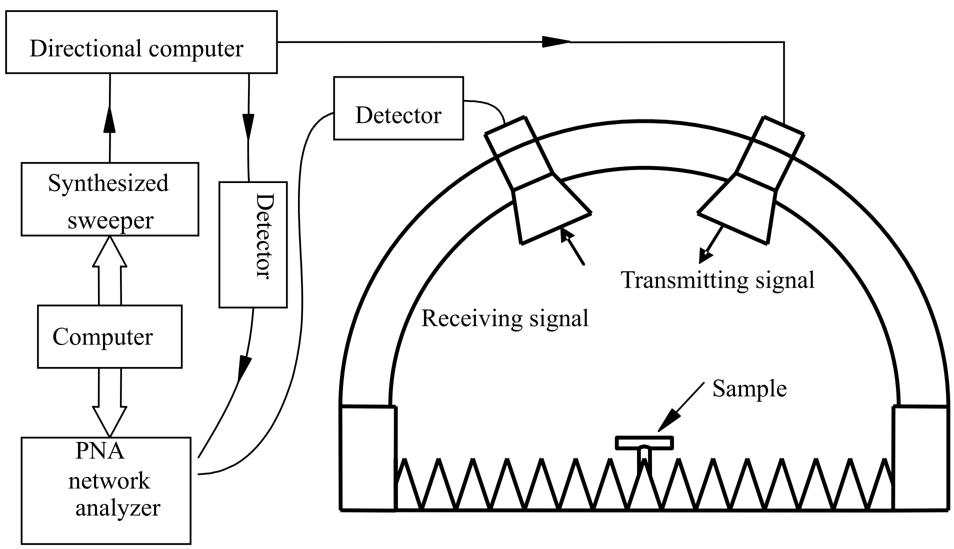
Short carbon fibers were first placed in glass beakers with part of the whole water to be used later to make sure they were completely immersed into water. The beakers were vibrated by ultrasonic wave for 10 min during which there were not any breakage of fibers. HEC was dissolved in water in the beakers and its mass fraction in the aqueous solution was around 1.70 %. The mixture was stirred by hand for 2 min and vibrated by ultrasonic wave for 10 min to ensure the uniform dispersion of carbon fibers in the transparent, sticky solution. During the process, the temperature of water was kept between 38 and 44 ℃ and the power of the ultrasonic wave source was 250 KW. A glass rod was used to stir the mixture intermediately. The defoamer TBP was added to eliminate air bubbles in the disperse system.

When cement, silicon fume, sand, and FDN were mixed uniformly in a J-160A rotary mixer with a flat beater for 3 min, the above prepared disperse system was poured into the mixer and the left water was added. The mixture was stirred for another 3 min. After pouring the mix into the 180 ×180 ×10 mm oiled square moulds, an external vibrator was used to facilitate compaction and decrease the amount of air bubbles. The samples were placed in a curing box and demolded after 24 hours and then allowed to cure in the curing box for 28 days. The temperature in the box was kept around 21±1 ℃ and the relative humidity was ≥96 %. Six pieces of samples were prepared.

Reflectivity measurement of CFRC samples

The samples must be dry before measurement to avoid the possible influence of moisture on the reflectivity. The Naval Research Laboratory (NRL) testing system was applied to measure the reflectivity as shown in Fig 1. The frequency range is between 8 and 18.2 GHz and the maximum movable attenuation is – 40 dB. The signal was transmitted from a network analyzer by way of a horn antenna. The other horn antenna received the reflecting signal. Then the signal was transmitted to the network analyzer. The distance between the sample and the horn mouths is approximately 1.88 meters. The sample was placed on a pedestal around which the floor was covered with standard pyramidal absorbers.

The tester was connected to an Aglient PNA Series Network Analyzer (E8362B，10MHz－20GHz, USA). The standard cement-sand sample without any carbon fibers was primarily measured for comparison. Five pieces of samples for different mass fractions of carbon fibers of 0.2 %, 0.4 %, 0.6 %, 0.8 %, and 1.0 % were measured. An aluminum plate sheet, which is exactly the same size as the sample, was used for the 0 dB calibration and it was placed tightly below the sample.



Results & Discussion

Figure 1. Simplified block diagram setup for reflectivity measurement by the NRL testing system

SEM observation and EDS analysis of CFRC samples

Fig.2 is a SEM image of the fracture surface of a standard cement-sand sample and the corresponding EDS graphics. The structure of the sample is relatively compact. So it can be inferred that the material exhibits good mechanical properties. When carbon fibers are uniformly dispersed in the cement matrix as shown in the left hand of Fig 3, the CFRC possesses not only good mechanical properties but also good electrical performances owing to the possible contact of carbon fibers one

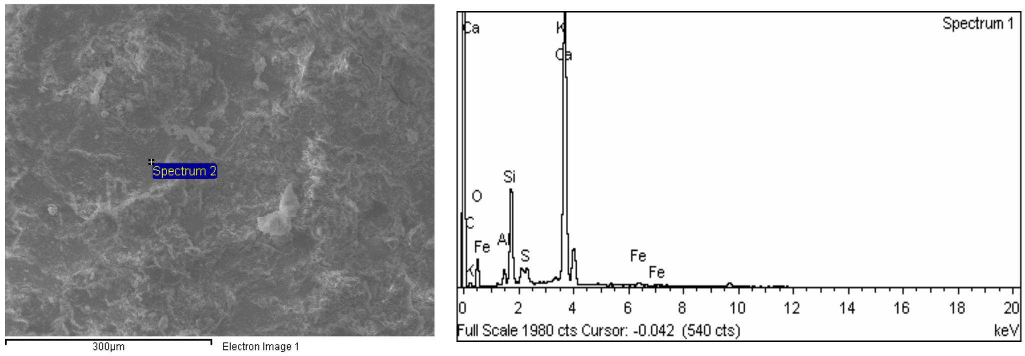


Figure 2. SEM image of the fracture surface of a standard cement-sand sample and corresponding EDS graphics

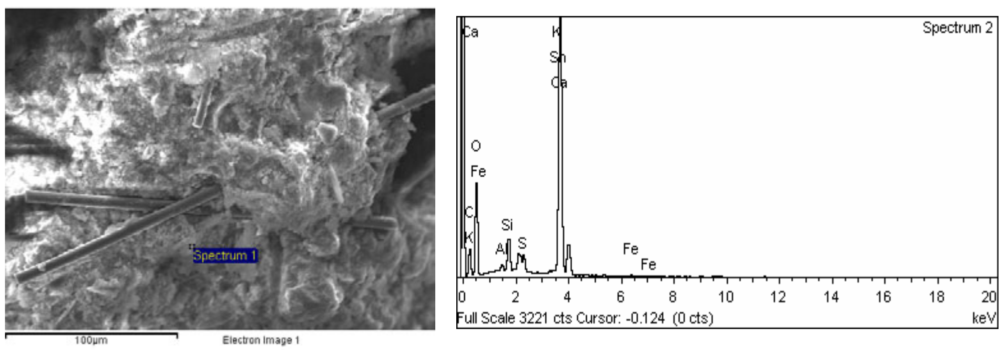


Figure 3. SEM image of the fracture surface of a CFRC sample and corresponding EDS graphics for good dispersion of carbon fibers in the cement matrix

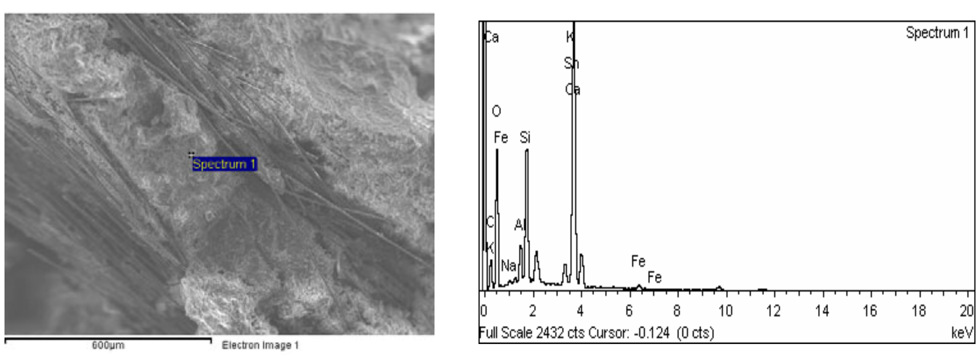


Figure 4. SEM image of the fracture surface of a CFRC sample and corresponding EDS graphics for poor dispersion of carbon fibers in the cement matrix

another. The contact of fibers or the very close distances (<10 nm) between fibers are beneficial to the formation of conductivity networks, which may further provide CFRC with ideal electromagnetic performances. However, when carbon fibers are not well distributed in the cement matrix as shown in the left hand of Fig.4, the CFRC composites exhibit poor mechanical properties with the increase of

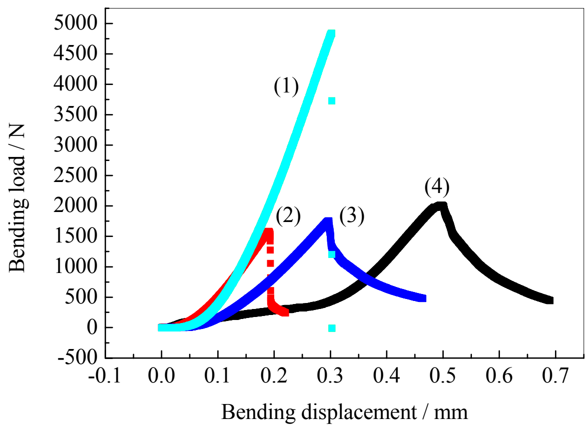


Figure 5. Relationship between bending load and displacement of CFRC samples

(1) A standard cement-sand sample without any carbon fibers
(2) A CFRC sample with a fiber mass fraction of 0.6 %
(3) A CFRC sample with a fiber mass fraction of 0.4 %
(4) A CFRC sample with a fiber mass fraction of 0.2 %

fiber mass fractions. Fig.5 shows the relationship between bending load and displacement when the mass fractions are changed. Curve (1) illustrates the result of a cement-sand sample without any carbon fibers. Curves (2)～(4) are the results of CFRC samples when carbon fibers are distributed in fascicule in the cement matrix with the mass fractions being 0.2 %, 0.4 % and 0.6 %, respectively. Clearly, the mechanical property of CFRC becomes poorer with the increasing of mass fractions. Besides, poor dispersion may exert negative influence on the reflectivity of the composites.

Major elements distribution such as Ca, Si, Al, O, and Fe in the standard sample is shown in the energy dispersive spectroscopy (EDS) graphics in Fig.2. Compared with the standard EDS graphics, major elements Si and Fe vary greatly when carbon fibers are homogenized in the cement matrix as shown in Fig.3. Compared with Fig.2 and Fig.3, the distribution of major elements Fe, Si, and AI still varies when carbon fibers exist in fascicule in the cement matrix as shown in Fig.4. Therefore, it is essential to emphasize the uniform dispersion of carbon fibers in the cement matrix to prepare homogenized CFRC samples.

Evaluation of Shielding Effectiveness of CFRC

According to Schelkunoff's theory [7－9], the shielding effectiveness (SE) of a material falls into three parts, R, A and M, as follows:

$$SE(dB) = R + A + M \qquad (1)$$

where A is the absorption of energy of the electromagnetic wave, R is the first reflection loss of energy, and M is a multi-reflection loss of energy. When A exceeds 10 dB, M can be negligible in the calculation. Thus Eq.1 becomes:

$$SE=R+A \qquad (2)$$

R can be expressed in two forms:

$$R(dB) = 354 + 10\log\left(\frac{\sigma}{f^3 \mu r^2}\right) \qquad (3)$$

$$\text{R(dB)}=20\log\left[\frac{0.462}{r\sqrt{\mu/f\sigma}}+0.316r\sqrt{\frac{f\sigma}{\mu}}+0.354\right] \quad (4)$$

R can be evaluated from Eq.3 for high impedance, namely, a greater electric field component in the electromagnetic wave, and from Eq.4 at low impedance, that is, a greater magnetic field component in the electromagnetic wave. In addition, absorption loss A can be evaluated from the equations as follows:

$$\text{A(dB)}=3.34\times10^{-3}t\sqrt{f\mu\sigma} \quad (5)$$

In Eqs.3−5, f is the incidental frequency of the electromagnetic wave (Hz), r is the distance from the emission source to the shielding material, σ is the electrical conductivity, μ is the magnetic transmissivity, and t is the thickness of the shielding material.

For CFRC composites, SE can be calculated from the Simon formula:

$$SE(dB)=50+10\log\left(\frac{1}{f\rho}\right)+1.7t\left(\sqrt{\frac{f}{\rho}}\right) \quad (6)$$

where ρ is the volume resistivity (Ωcm) at room temperature, t is the thickness of the sample (cm), and f is the measurement frequency (MHz). Obviously, SE is a function of sample resistivity, thickness and measurement frequency. The effect of multiple reflections is omitted in this empirical equation. The first two terms combined can estimate the shielding effect by reflection loss R and the last term represents the part by absorption A. The sample thickness in this study is 10 mm and R is mostly emphasized and measured through reflectivity.

For further explanation, the parameters of carbon-fiber-reinforced composites after carbon fibers are treated at high temperatures are provided in Table 2 for reference. ε_r is relative permittivity, $tg\delta_t$ is medium loss tangent, S_{11} is scattering parameter of vertical thermal radiation of electromagnetic wave, S_{21} is parallel scattering parameter, and RL is the reflectivity of electromagnetic waves. The table shows that the real number of the relative dielectric constant of the composites ($\varepsilon_r=\varepsilon/\varepsilon_0$) ε_r' is far more than 1 while the relative magnetic permeability ($\mu_r=\mu/\mu_0$) is approximately equal to 1. Therefore, the impedance of the composites is far less than the wave impedance of the free space. In addition, the scattering parameter S_{21} is less while S_{11} is larger and the interface reflection is above 93 %. So, it can be inferred that the reflectivity in the frequency range of 8.2～12 GHz is above -0.9 dB when the electromagnetic waves are upon the composites vertically. Consequently, carbon fibers almost reflect completely microwaves when they are treated at high temperatures and they don’t absorb waves such that they are often used as reflection base plate of absorbing materials [8－11].

Table 2. Electromagnetic parameters of carbon-fiber-reinforced composites [9]

Frequency/ GHz	ε_r'	$tg\delta_t$	S_{11} / dB	S_{21} / dB	RL / %
8.2	294	0.57	-0.31	-24.93	93.5
9.0	284	0.62	-0.35	-24.72	93.0
10.0	256	0.75	-0.21	-24.96	93.5
11.0	188	1.35	-0.35	-25.42	94.5
12.0	102	2.42	-0.36	-25.89	95.5

Reflectivity of CFRC samples

The reflectivity vs frequency curves of the CFRC samples measured through the NRL system are shown, respectively, in the following figures. When the electrical field direction is parallel to the fiber direction, carbon fibers reflect microwaves. Their behaviors are similar to metals. When the electrical field direction is perpendicular or oblique to the fiber orientation, they exhibit the properties of absorbing microwaves under the circumstances of which they are the dielectric loss medium [12—14]. In this study, carbon fibers are distributed at random in the cement matrix such that the following measured curves are the net results of the interaction between reflection and absorption.

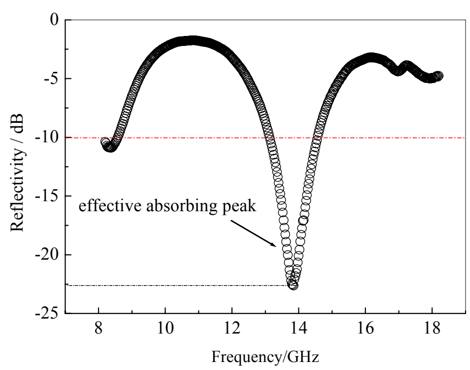


Figure 6. Reflectivity vs frequency curve of a standard cement-sand sample without any carbon fibers

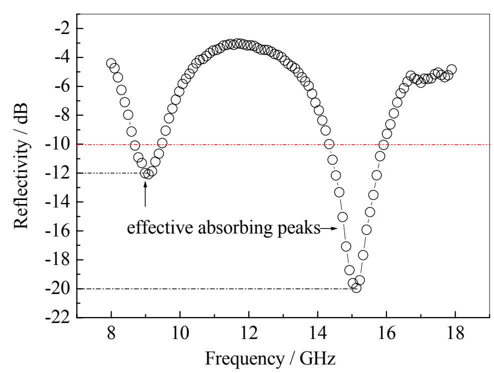
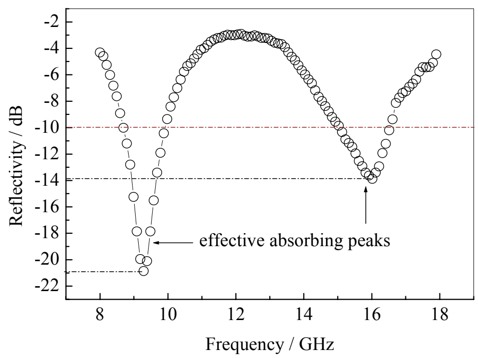


Figure7. Reflectivity as a function of frequency for a fiber mass fraction of 0.2 %

Fig.6 shows the reflectivity curve of a standard cement-sand sample without any carbon fibers. There is an apparent sharp absorbing peak near 14 GHz, at which the reflectivity is –22.5 dB, far less than –10 dB, demonstrating strong wave-absorbing performances. When carbon fivers are added in and their mass fraction is 0.2 %, two absorbing peaks appear, respectively, in the frequency of 9 GHz at which the reflectivity is –12 dB and in the frequency of 15 GHz at which the reflectivity is –20 dB as shown in Fig.7. Both reflectivity data are below –10 dB and there are properties of absorbing electromagnetic waves.



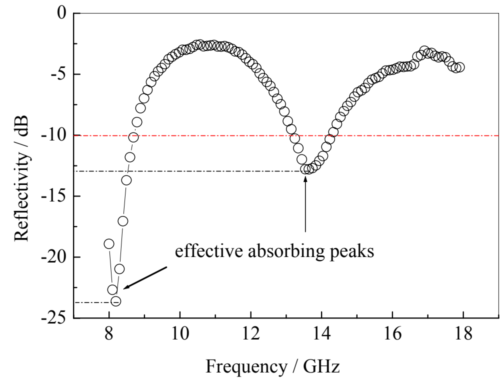
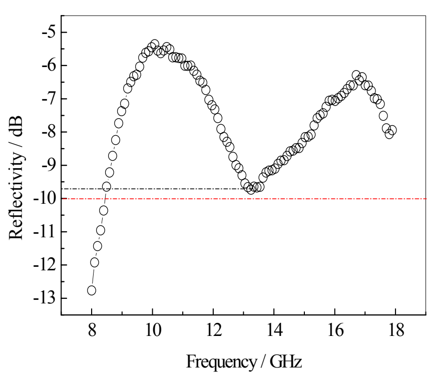


Figure 8. Reflectivity as a function of frequency for a fiber mass fraction of 0.4 %

Figure 9. Reflectivity as a function of frequency for a fiber mass fraction of 0.6 %

When the mass fraction reaches 0.4 %, there are still two apparent absorbing peaks as shown in Fig.8: one is near the frequency of 9 GHz at which the reflectivity is –21 dB and the other appears in the frequency of 16 GHz at which the reflectivity is almost –14 dB. Still, both the reflectivity data are less than –10 dB and the wave-absorbing properties exist. When the mass fraction rises to 0.6 % as shown in Fig.9, still two apparent absorbing peaks exist: one emerges near the frequency of 8 GHz at which the reflectivity is –23.7 dB and the other occurs in the frequency range of 13～14 GHz in which the reflectivity is –12.8 dB. Still, there are strong absorbing performances of electromagnetic waves.

The reflectivity curve, however, varies greatly when the mass fraction reaches 0.8 % (see Fig.10). In this figure, one absorbing peak with the reflectivity of –9.8 dB takes place above –10 dB and there are wave-reflecting performances. When the mass fraction finally increases to 1.0 %, no absorbing peaks below –10 dB occur, though there are two apparent absorbing peaks with the reflectivity of –7.25 dB and –7.52 dB. In other words, when the mass fractions increase to 0.8 % and 1.0 %, the CFRC exhibits wave-reflecting properties dominantly.



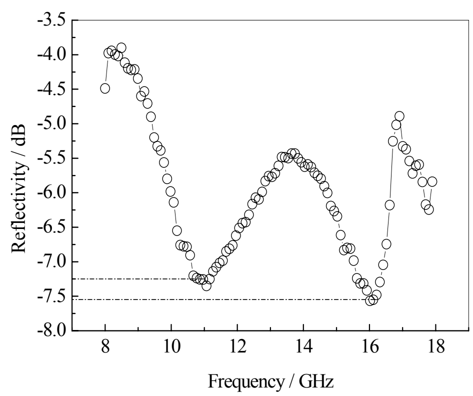


Figure 10. Reflectivity as a function of frequency for a fiber mass fraction of 0.8 %

Figure 11. Reflectivity as a function of frequency for a fiber mass fraction of 1.0 %

The measured minimum reflectivity data and the SE values that are theoretically evaluated in accordance with formula 6 are listed in Table 3, on the basis of which the correspondent curve between reflectivity and mass fractions as well as the curve between SE and mass fractions is drawn in Fig.12. It can be seen from Fig.12 (a) that the reflectivity decreases gradually starting with the percentage of 0.2

% with the increasing of mass fraction till the percentage of 0.6 %, after which the reflectivity increases abruptly as the mass fraction rises. Before 0.8 %, the CFRC exhibits mainly wave-absorbing properties and after 0.8 % it exhibits mainly wave-reflecting properties. However, Fig.12 (b) shows that prior to the percentage of 0.6 %, SE decreases steeply as the mass fraction rises. After this point, SE increases linearly.

Table 3. The measured minimum reflectivity and the evaluated SE data of CFRC for different mass fractions of carbon fibers

No.	Mass fraction of carbon fiber / %	Minimum reflectivity / dB	Evaluated SE values / dB	Reflectivity below –10dB / GHz
1	0	–22.5	– 4.95	Existent
2	0.2	–20.0	– 4.84	Existent
3	0.4	–21.0	– 5.29	Existent
4	0.6	– 23.7	– 5.36	Existent
5	0.8	– 9.7	– 5.04	Nonexistent
6	1.0	–7.5	– 4.74	Nonexistent

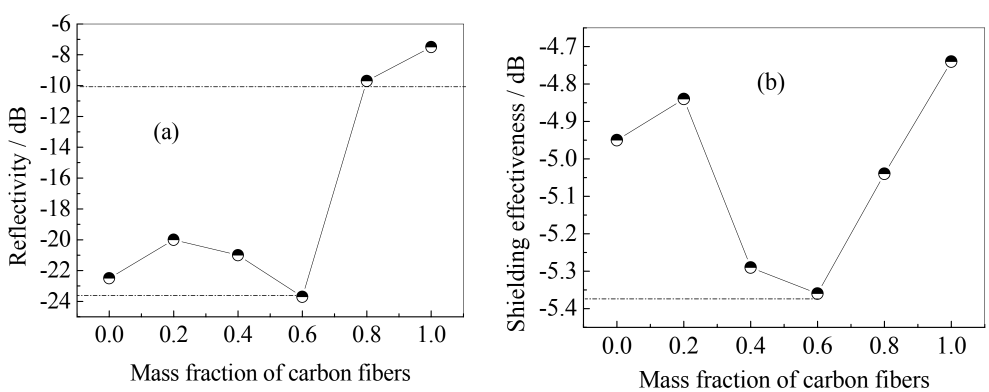


Figure 12. Reflectivity as a function of fiber mass fraction (a) and SE as a function of fiber mass fraction (b)

Generally, a relatively high dB value is desired for SE transmission measurements, indicating that the energy is being effectively attenuated by CFRC due to a combination of reflection and absorption, which further indicates that the composites would be a good EMI shielding material. However, the amount of energy absorbed by fibers is related to the skin depth of the fiber. The electromagnetic wave only penetrates a shallow depth into the fiber. This phenomenon is called the skin effect [14—16]. The SE in transmission is often adopted to rank the effectiveness of a composite, but reflectivity is also conveniently used to reveal it indirectly. The higher the dB, the better the wave-reflecting performances are. The lower the dB, the better the wave-absorbing performances are. A lower dB value is desired for attenuation due to reflection, showing that the energy is being effectively reflected off the incident surface of the composites. Shielding reflection losses are a function of the electrical conductivity and magnetic permeability and the frequency of the incident electromagnetic energy [14].

Conclusions

(1) The EMI of CFRC composites can be assessed through reflectivity. The reflectivity starts to decrease with the increasing of mass fraction of carbon fibers at the percentage of 0.2 %. When the percentage moves to 0.6 %, the minimum reflectivity appears. It is –23.7 dB and there are mainly wave-absorbing performances. After 0.6 %, the reflectivity increases abruptly with the increasing of fiber mass fractions till the percentage of 0.8 %, after which it increases gradually.

(2) SE tends to decrease steeply at the percentage of 0.2 %. After 0.4 %, it increases slowly. Still, when the percentage moves to 0.6 %, the minimum SE value occurs. It reads –5.36 dB and there are dominantly wave-absorbing properties. After 0.6 %, SE increases linearly.

(3) Compared with the reflectivity –22.5 dB of a standard cement-sand sample without any carbon fibers, CFRC is a good shielding material from the viewpoint of wave reflection. In addition, the length of carbon fibers and the additives inside the CFRC may exert influence over the reflectivity, which needs to be validated in later experiments.

Acknowledgements

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