Study on mechanism of electromagnetic shielding effectiveness of carbon nanofibers reinforced cement concrete

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Abstract. In this paper, five groups of cement concrete specimens reinforced by carbon nanofibers (CNFs) were prepared with different fiber content of 0%, 0.1%, 0.2%, 0.3% and 0.5%, the electromagnetic shielding effectiveness (SE) and the mechanism of shielding were analyzed. The results show that, when the frequency of electromagnetic wave is higher than 2 GHz, with the increase of frequency, the improvement gradually increases; When the frequency is 18 GHz, the SE reaches the maximum; CNFs can improve the SE of concrete material by improving its conductivity and the loss of electromagnetic wave.

1. Introduction
Countless wars have proved that protective engineering plays an irreplaceable role in the war that preserving the safety of its own personnel and equipment. With the rapid development of electronic technology and the continuous innovation of electromagnetic technology, the form of modern war has been changed, that from the traditional weapon attack to the damage and interference of command and communication system, electronic equipment and information weapons. Various new kind of radars [1, 2], advanced detectors [3, 4] and even electromagnetic wave weapons [5-7] have come out one after another, which puts forward new and higher requirements for electromagnetic shielding technology of protective engineering. Electromagnetic wave can bring serious interference and damage to electronic equipment, especially to C4ISR system [8, 9], causing damage or instantaneous failure of electronic components, thus affecting the accuracy of data link transmission. In the modern information war, the threat of electromagnetic interference to protective engineering is becoming more and more serious. Therefore, improving the electromagnetic protection capability of the protective engineering has gradually become an important direction in the research of protective engineering.

Facing the "soft" damage of electromagnetic interference, the develop and selection of new materials is an important direction in current research. Carbon nanofibers (CNFs) is a kind of discontinuous nano-sized graphite fiber that prepared by cracking gaseous hydrocarbons [10, 11], which has the intrinsic properties of carbon fibers and various effects of nano materials [12-14]. CNFs can absorb and consume a lot of external electromagnetic waves at the same time, which has good
electromagnetic shielding effectiveness [15-17]. Based on this, five groups of carbon nanofibers reinforced concrete (CNFC) specimens were prepared by adding different content of CNFs, and the HTEMG8003 electromagnetic compatibility test system is used to analyze the electromagnetic shielding effectiveness (SE) of CNFC, and the shielding mechanism is further discussed.

2. Experiment
The test of SE were carried out in strict accordance with the Measuring methods for shielding effectiveness of electromagnetic shielding materials (GJB 8820-2015, in Chinese). The detecting position is the centre of the specimen, the test device is shown in Figure 1, test environment temperature is 19 ℃ and the humidity RH is 62%, which meets the requirements of the standard, the test frequency points are 30 MHz, 50 MHz, 100 MHz, 150 MHz, 200 MHz, 300 MHz, 500 MHz, 800 MHz, 1 GHz, 2 GHz, 5 GHz, 7 GHz, 10 GHz, 12 GHz, 15 GHz and 18 GHz.

According to the standard requirements, the size of the window for electromagnetic shielding test is 600 mm×600 mm, so the geometric dimension of the specimen is designed as 700 mm×700 mm×20 mm, as shown in Figure 2. Since the specimens are placed in the window of the shielding room for testing, they should be closely fitted with the window as much as possible, thus the surfaces of specimens were polished by concrete grinding machine after the curing. In order to facilitate the comparative analysis, a control group was set up in this experiment, i.e. CNFs content is 0%, marked as PC, and there were four test groups, i.e. CNFs content are 0.1%, 0.2%, 0.3% and 0.5%, which marked as CNFC01, CNFC02, CNFC03 and CNFC05 respectively.

To ensure the accuracy of the test, the specimens and the window should be closely fitted to avoid the leakage of electromagnetic wave. Because the specimens are connected with the window in a hanging way and the corresponding position of them are punched, thus the redundant holes are sealed with copper tape, the contact edge of specimens and the window is also pasted with copper tape to make the edge in a sealed state for prevent electromagnetic wave leakage, and to ensure the effective conduction connected between the surfaces of specimens and the surrounding of the shielding room at the same time, as shown in Figure 3.

3. Experiment results
In this paper, the laws of SE with electromagnetic wave frequency that change in a wide frequency range from 30 MHz to 18 GHz of CNFC is studied, as shown in Figure 4, 16 frequency points including 30 MHz, 50 MHz and 1 GHz are tested.
Figure 4. Relationship between SE and electromagnetic wave frequency

It can be seen from the Figure 4 that: (1) at a certain frequency, the larger the content of CNFs, the larger the SE of each measurement point, which shows that the addition of CNFs has an obvious enhancement effect on the SE, and especially at a higher frequency, the content of CNFs has a great influence on the absorption properties; (2) With the increase of frequency, the SE of PC is basically unchanged, while the shielding performance of CNFC is gradually improved, which shows that the frequency has a positive impact on the electromagnetic shielding performance of CNFC; (3) In the frequency range of 30 MHz–2 GHz, the SE is not high in general, the maximum value is 21.5 dB, and the SE fluctuates greatly in this frequency range, which shows that the improvement effect of CNFs on the efficiency of electromagnetic shielding rate is not obvious when the frequency is relatively low; (4) When the frequency exceeds 2 GHz, the increase of SE tends to be stable with the increase of frequency, and when the frequency reaches 18 GHz, the maximum value is 67 dB, which is increased by 54.0 dB, this indicates that when the frequency is greater than 2 GHz, the SE of concrete is significantly improved by CNFs.

4. Mechanism analysis

4.1. Effect of material conductivity

CNFs is a kind of carbon material, which has excellent electrical conductivity. Therefore, the addition of fibers can effectively reduce the resistance of concrete and significantly improve its electrical conductivity [18]. The electric conductivity of the material is an important factor that affects the electromagnetic shielding effectiveness, for shielding materials with good conductivity, eddy current will occur when the electromagnetic wave is transmitted to their surfaces, as shown in Figure 5. The formation of eddy current can produce an anti-magnetic field, so it can counteract part of electromagnetic wave, and eddy current is accompanied by the generation of heat, which transforms part of electromagnetic energy into thermal energy, and the electromagnetic energy is further consumed, thus the addition of CNFs can get certain effects in electromagnetic shielding effect by improving the electrical conductivity of concrete. In addition, it should be noted that the eddy current generally occurs in the high frequency band, and only appears on the surface of the material [19], and under the normal circumstances, there loss of eddy current to electromagnetic waves is relatively low, and eddy current has a high requirement on the conductivity of materials.
Figure 5. Schematic diagram of eddy current in shielding materials

The conductivity of the material also affects its impedance matching with the electromagnetic wave, the better the impedance matching condition, the more electromagnetic wave the material absorbs, otherwise, the more electromagnetic wave the material reflects. Therefore, the shielding material with better conductivity can not only produce the loss of electromagnetic wave through eddy current, but also can shield electromagnetic wave by means of the reflection of material surface. Figure 6 shows the change laws of reflectivity of specimens with the electromagnetic wave frequency, it can be seen from the figure that the addition of CNFs can greatly improve the reflectivity $\Phi$ of concrete to electromagnetic wave. In the entirety, with the increase of fiber content, $\Phi$ gradually increases.

4.2. Loss of the material itself to electromagnetic waves

According to the analysis of the electromagnetic shielding principle, the loss of electromagnetic wave is mainly divided into three parts: reflection loss ($SE_R$), absorption loss ($SE_A$) and multiple reflection loss ($SE_M$), the parameters that reflect these three kinds of losses are dielectric constant $\varepsilon$ and magnetic permeability $\mu$. Usually, for most materials, $\varepsilon$ and $\mu$ are expressed in complex form [20]:

$$
\begin{align*}
\varepsilon &= \varepsilon' - j\varepsilon'' \\
\mu &= \mu' - j\mu''
\end{align*}
$$

The real and imaginary parts of $\varepsilon$ and $\mu$ are related to the frequency of electromagnetic wave, the real part represents the storage capacity of materials for electromagnetic wave energy, the larger the $\varepsilon'$ and $\mu'$ are, the stronger the ability of the material to store electromagnetic wave energy is. The imaginary part characterizes the loss ability of material to electromagnetic wave, and the larger the $\varepsilon''$ and $\mu''$ are, the stronger the ability of the material to lose electromagnetic energy is.

The electric loss $\omega_e$ and magnetic loss $\omega_m$ of the unit volume part of the material to the electromagnetic wave can be expressed as:

$$
\begin{align*}
\omega_e &= \frac{2\pi f \varepsilon'' \mu''}{\mu'' \varepsilon'' + \varepsilon'' \mu''} \\
\omega_m &= \frac{2\pi f \varepsilon' \mu'}{\mu' \varepsilon' + \varepsilon' \mu'}
\end{align*}
$$
\[ \omega_e = \text{Re} \left[ \frac{1}{2} \mathbf{E} \cdot \mathbf{j}^* \right] = \text{Re} \left[ -\frac{1}{2} j \omega \varepsilon' \mathbf{E}^* \cdot \mathbf{E}^* \right] = \text{Re} \left[ -\frac{1}{2} j \omega (\varepsilon' + j \varepsilon'') \mathbf{E}^2 \right] \]
\[ = \text{Re} \left[ \frac{1}{2} \omega \varepsilon'' \mathbf{E}^2 - j \frac{1}{2} \omega \varepsilon' \mathbf{E}^2 \right] = \frac{1}{2} \omega \varepsilon'' \mathbf{E}^2 \]  
(2)

\[ \omega_m = \text{Re} \left[ \frac{1}{2} \mathbf{B} \cdot \mathbf{H}^* \right] = \text{Re} \left[ \frac{1}{2} j \omega \mu \mathbf{H}^* \cdot \mathbf{H}^* \right] = \text{Re} \left[ \frac{1}{2} j \omega (\mu' - j \mu'') \mathbf{H}^* \cdot \mathbf{H}^* \right] \]
\[ = \text{Re} \left[ \frac{1}{2} \omega \mu'' \mathbf{H}^2 - j \frac{1}{2} \omega \mu' \mathbf{H}^2 \right] = \frac{1}{2} \omega \mu'' \mathbf{H}^2 \]  
(3)

Where \( E \) and \( H \) are the amplitude values of electric field and magnetic field respectively.

Therefore, it can be seen from the above two equations that the \( \omega_e \) and \( \omega_m \) of the unit volume part of the material are directly proportional to \( \varepsilon'' \) and \( \mu'' \), respectively.

The loss of material to electromagnetic wave mainly depends on the \( e \) and \( \mu \), while the \( e \) and \( \mu \) vary greatly with different material types. Meanwhile, \( e \) and \( \mu \) are greatly affected by the frequency of electromagnetic wave, and the response of materials to electromagnetic waves varies with frequency. In general, the imaginary parts of \( e \) and \( \mu \) are smaller than the real parts, and when the imaginary part of a material is much smaller than the real part, that is, the imaginary part is negligible compared with the real part, which means the material does not have the ability of absorbing wave, in other words, the loss of electromagnetic wave can be ignored, and the response to electromagnetic wave mainly plays the role of storage energy, this kind of material is called transparent material. When the imaginary parts of \( e \) and \( \mu \) cannot be ignored, the material has the ability of absorbing and storing electromagnetic wave at the same time, which is called absorbing material. Therefore, a good electromagnetic shielding material not only has a high reflection ability for electromagnetic waves, but also has a good loss ability for the electromagnetic waves that entered the material.

In conclusion, it can be seen that after reinforced by CNFs, the reflection ability and internal loss of concrete to electromagnetic wave are both significantly enhanced. Therefore, the significant improvement of electromagnetic shielding of concrete by CNFs is feasible in the field of protective engineering, and has a very broad application prospect.

5. Conclusions

Five groups of CNFC with different CNFs content of 0%, 0.1%, 0.2%, 0.3% and 0.5% were prepared in this paper, and the electromagnetic shielding effectiveness and mechanism were analyzed, the main conclusions are as follows:

1. At a certain frequency, with the increase of the content of CNFs, the SE of CNFC increases gradually, which means the CNFs can improve the electromagnetic shielding performance of concrete obviously.

2. When the frequency is lower than 2 GHz, the SE of materials fluctuates up and down with the increase of frequency; When the frequency is higher than 2 GHz, the SE of PC does not change much with the increase of frequency, while the SE of CNFC is significantly improved, and the higher the content of CNFs, the more obvious the improvement effect.

3. CNFs can not only improve the electrical conductivity of concrete, but also enhance its loss of electromagnetic wave energy, thus significantly improving the electromagnetic shielding efficiency of concrete.

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