Preparation of a novel foamed concrete modified with carbon fiber and graphite:

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Abstract

In this paper, foam concrete is modified using graphite and carbon fiber as absorbents. The mechanical properties of the foam concrete are analysed in conjunction with hydration products, pore size distribution based on SEM test and XCT test. Further, the resistivity, complex permittivity and complex permeability are tested. The results demonstrate that carbon fiber enhance the proportion of pores with diameters less than 200\,\mu m in foam concrete, thereby substantially enhancing its flexural strength. Besides, adding graphite offsets the initial retardation of sulfoaluminate cement hydration induced by carbon fibers, which increases the average pore size of carbon fiber-reinforced foam concrete, reducing the compressive strength. The addition of carbon fibers at a concentration of 0.6wt.\% achieves the percolation threshold, akin to scenarios with singular fiber incorporation. Exceeding 2wt\% graphite content results in negligible influence on the conductivity of the carbon fiber-reinforced foam concrete.

Preparation of a novel foamed concrete modified with carbon fiber and graphite: Mechanical, electro-magnetic and microstructural characteristics based on X-CT

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Abstract: In this paper, foam concrete is modified using graphite and carbon fiber as absorbents. The mechanical properties of the foam concrete are analysed in conjunction with hydration products, pore size distribution based on SEM test and XCT test. Further, the resistivity, complex permittivity and complex permeability are tested. The results demonstrate that carbon fiber enhance the proportion of pores with diameters less than 200\,\mu m in foam concrete, thereby substantially enhancing its flexural strength. Besides, adding graphite offsets the initial retardation of sulfoaluminate cement hydration induced by carbon fibers, which increases the average pore size of carbon fiber-reinforced foam concrete, reducing the compressive strength. The addition of carbon fibers at a concentration of 0.6wt.\% achieves the percolation threshold, akin to scenarios with singular fiber incorporation. Exceeding 2wt\% graphite content results in negligible influence on the conductivity of the carbon fiber-reinforced foam concrete. The synergistic integration of graphite and carbon fibers significantly enhances the electromagnetic wave absorption performance of the composite. At a thickness of 6 mm, the material exhibits an effective bandwidth where the reflection loss is less than -10 dB, extending up to 2.5 GHz, which constitutes 52.08\% of the tested frequency spectrum.

Keywords: carbon fiber(D); X-CT(B); magnetic property(C)

1. Introduction

Nowadays, rapid development has been achieved in modern wireless communication technology and the electronic equipment has been applied widely, which does improve the convenience of our life. However,
electromagnetic radiation has become an inevitable by-product\cite{1,2} which not only causes the leakage of important information\cite{3}, but also harms human health\cite{4,5}. In order to reduce electromagnetic radiation in the environment, wave-absorbing materials have been widely used in construction\cite{6}, and cement-based materials, as common building materials, have good environmental adaptability, low cost, and easy availability\cite{7}. Foam concrete, as a kind of cement-based material with rich pores inside, is often used for building partitions and roof systems\cite{8}. If absorbents are added in it, it can make buildings have functions of thermal insulation, fire protection and electromagnetic wave absorption.

According to transmission line theory, effective impedance matching is a prerequisite for materials to absorb electromagnetic waves\cite{9}. Traditional cement-based materials have a dense structure and poor impedance matching, making it difficult for electromagnetic waves to enter\cite{10}. With low density and low dielectric constant, porous materials such as expanded polystyrene\cite{11,12}, hollow glass beads\cite{13}, and expanded perlite\cite{14,15} are often incorporated into cement-based materials to improve impedance matching with free space\cite{16,17}. However, foam concrete itself can extend the transmission length of incident waves and simplify the preparation process. The increase in the number of electromagnetic wave reflection, scattering, and interference also strengthens the loss of electromagnetic wave energy\cite{18}.

Furthermore, the dielectric effect and magnetic effect loss of absorbents are key factors affecting the absorption performance of electromagnetic waves\cite{19,20}. In terms of loss mechanism, the absorbents added to cement-based materials can be divided into magnetic media type\cite{21,22}, resistive type\cite{23,24}, dielectric type, and novel materials combining various loss methods\cite{25,26}. As the resistive absorbent, graphite and carbon fiber can attenuate and absorb electromagnetic waves through the electronic polarization or interface polarization of the medium, and the cost is low and the conductivity and alkali resistance are excellent\cite{27}. Xin et al.\cite{28} incorporated graphite into foam concrete to study the effects of graphite content, foaming agent content, surface roughness, and age and moisture content of the specimen on electromagnetic wave absorption performance. The results show that when 15wt.% graphite is added, the percolation threshold is reached. When it exceeds 15wt.%, the reflectivity of electromagnetic waves is greatly increased but the porosity and compressive strength are reduced. Shi et al.\cite{29} combined iron powder and graphite with MnZn ferritic cement-based materials. The research shows that adding graphite can decrease the minimal reflection loss of gelled composites, and the mechanical strength can meet the requirements of most construction applications. Wang et al.\cite{30} mixed graphite and carbon fiber into cement, and the maximum absorption peak (with the reflectivity of -5.67 dB) appeared in the 12.5-18 GHz frequency range. Numerical simulations were conducted using ANSYS to verify the experimental conclusions.

Currently, there are few studies and applications of foam concrete in the field of absorbing electromagnetic waves\cite{31}. In addition, due to the internal pore structure, the mechanical properties of foam concrete are more susceptible to the influence of absorbing agent, and its absorbing function will be limited in practical engineering due to the defects of the material itself\cite{32}.

In this study, foam concrete is used as the matrix, and graphite and carbon fiber are used as admixtures to prepare wave-absorbing foam concrete. The effects of single doped carbon fiber and graphite-carbon fiber compound doping on the mechanical-electro-magnetic properties of foam concrete are clarified. XRD, XCT and SEM tests are performed to analyze the hydration process and microstructure of foam concrete.

2. Experimental

2.1 Raw materials

The 42.5 sulfoaluminate cement used for the test is offered by Tangshan Polar Bear Building Materials Co., Ltd. Its chemical composition is given in Table 1. Its physical properties are given in Table 2. The foamer is HTW-1 composite protein foamer. The carbon fiber is offered by Taili Carbon Fiber Co., Ltd., with a length of 3 mm and a fiber diameter of 7 μm. The graphite is provided by Baichuan Environmental Engineering Co., Ltd., with a grain size of 23 μm. The water reducing agent is a powdered polycarboxylic acid water
reducing agent. The hydroxypropyl methylcellulose used for the test is offered by Jinzhou Fuqiang Fine Chemical Co., Ltd. The tap water is adopted.

2.2 Specimen preparation
Specific preparation process is as follows:
1) Take the water reducing agent, graphite, carbon fiber and cement according to the design mix ratio, and pour them into the stirring pot in batches and stir slowly for 180s;
2) Prepare a mixture of hydroxypropyl methylcellulose with water and add it to the stirring pot, and then stir slowly for 120 s and then quickly for 90 s;
3) The foaming agent solution (the mass ratio of foaming agent to water is 1 : 40) is foamed by a foaming machine, and the prepared foam is shown in figure 1. Add it to the mixing bowl and mix it well with the slurry that has been stirred;
4) Test the wet density of foam concrete before pouring. The design wet density of foam concrete is 600 kg/m$^3$;
5) After 24 hours of pouring, the mold is removed and the specimens are placed in cure chamber (20±2°C, RH [?95%]) to the desired age. The mix ratio is shown in Table 3, and the ratio of water to cement is 0.5.

2.3 Testing methods

2.3.1 Mechanical property test
The compressive strength of the foam concrete is measured based on JG/T 266-2011 Foam concrete, and the flexural strength is measured based on GB/T 17671-2021 Test method of cement mortar strength. Each group is tested for three samples and then calculate the average value.

2.3.2 XRD test
The 2cm$^3$ sample is hammered inside the specimen and immersed in anhydrous ethanol for 7 days. Then, dry it in a drying oven with the temperature of 50degC to a constant weight, and ground it into powder. Further, it is sieved through a 200 mesh sieve to obtain the powder.. Finally, the XRD test is conducted with an Empyrean polycrystal X-ray diffraction analyzer whose the diffractometer scan range is 5 to 90deg.

2.3.3 SEM test
The surface of the foam concrete sample is sawn off and immersed in anhydrous ethanol for 7 days. Then, dry it in a drying oven to a constant weight with a temperature of 50. It is polished with sandpaper into a flake specimen (about 1cm x 1cm in size and 2mm thick) and then cleaned with a brush to determine the observation surface. The instrument is TESCAN MIRA LMS scanning electron microscope, and the analysis software is Image j.

2.3.4 XCT test
A cube of 1 cm$^3$ is cut in the center of the foam concrete volume for XCT test. The test instrument is Xradia 510 Versa high-resolution three-dimensional X-ray microscope produced by Carl Zeiss. The software used to analyze the data is Dragonfly pro.

2.3.5 Conductivity test
Two copper meshes are set vertically inside the sample after casting as electrode plates. The size of the copper mesh is 3cmx5cm. The resistance $R$ of the sample is tested after 28 days of curing. The resistivity of the sample is calculated by Eq. 1, and the conductivity is calculated by Eq. 2. $S$ is the contact area between copper mesh and slurry, which is 9cm$^2$ in this study. $L$ is the distance between two copper meshes. The instrument used is an electronic multimeter produced by Elecco Electric Co., Ltd.

\[
\rho = \frac{RS}{L} \quad \text{(Eq. 1)}
\]
\[ k = \frac{1}{\rho} \text{ (Eq. 2)} \]

### 2.3.6 Electromagnetic parameter test

The specimen for the electromagnetic parameter test is a coaxial ring. The outer diameter is 23mm, the inner diameter 10mm, and the height 20mm. Before testing, polish the surface of the specimen cured to 28 days until there are no burrs and chamfers. Then, it is dried in a drying oven to a constant weight with the temperature of 50\(^\circ\)C and then kept in a dry environment. The test frequency band of electromagnetic parameters is 0.2 to 5 GHz, and the coaxial transmission/reflection method is adopted by using a vector network analyzer produced by China Ceyear Technology Co., Ltd.

### 3. Results and discussions

#### 3.1 Compressive strength

The compressive strength of the foam concrete after adding different amounts of carbon fiber is displayed in Figure 2.

From this figure, whether at the age of 3d or 28d, the compressive strengths of the four groups of specimens change with the same trend: group C1 > group C2 > group O > group C3. Compared with that of group O, the compressive strength of group C1 at 3d and 28d increases by 0.34 MPa and 0.22 MPa, respectively. However, the strength of group C2 increases slightly at 3d and 28d compared with that of group O, only 0.07 MPa and 0.02 MPa, respectively. As more carbon fiber is added, the compressive strength drops dramatically. The compressive strength of group C3 at 3d is only 1.77 MPa, decreased by 41.58% compared to that of group O at the same age. Thus, the addition of carbon fiber in the range of 0.6wt.% slightly improves the compressive strength of specimens, and the enhancement effect is relatively good when the content is 0.3wt.%. Lu et al.[33] added carbon fibers to the concrete matrix and found that as the amount of carbon fiber admixture increased, the strength of the concrete showed a tendency to increase and then decrease. This is because the carbon fiber with low content can be evenly distributed in the slurry and fully bonded to the hydration products. And the elastic modulus of carbon fiber is much higher than that of foam concrete, effectively inhibiting the growth of cracks in foam concrete and improving compressive strength. However, when the carbon fiber content exceeds a certain value, it is easy to agglomerate during stirring due to its Van der Waals force and further reduces the processability of the foam concrete slurry. It also damages the pore structure inside the foam concrete, increases the connecting holes, and causes stress concentration after being exposed to external forces.

Figure 3 exhibited the compressive strength of graphite-carbon fiber foam concrete. It follows that the compressive strengths of the three groups with the addition of graphite and carbon fiber decrease at different ages. The compressive strength of group C2S2 decreases the most compared to that of group O at 3d, accounting for 84.82\% of group O. At 28d, the compressive strength of group C2S3 decreases the most compared to that of group O, accounting for 81.08\% of group O. The three groups have similar compressive strength values. It indicates that when the content of graphite is less than 10wt.\%, the addition of graphite and carbon fiber, little effect will be generated on the compressive strength. As can be seen from the previous article, the compressive strength of group C2 with 0.6wt.% carbon fiber is slightly higher than that of group O, proving that graphite is unfavorable to the compressive strength. This is because graphite is an inert material with poor cementing ability[34]. In the preparation process of the composite group specimens, we also find that the consistency of the cement slurry increases with increasing graphite content. With the large specific surface area of graphite, a large amount of free water is absorbed, with the result that the carbon fiber cannot be dispersed in the cement slurry uniformly and causing agglomeration. It adversely affects the compressive strength of the specimens.

#### 3.2 Flexural strength

Figure 4 displays the flexural strength of carbon fiber foam concrete at different ages.
The flexural strength of group C2 with 0.6wt.% carbon fiber increases significantly and reaches 3.6 MPa at 28d, 188.62% higher than that of group O at the same age. The strength values at different ages are sorted from large to small as group C2 > group C3 > group C1 > group O. It indicates that there is an optimal dosage of carbon fiber in improving the flexural strength. Han et al.[35] found that the enhancement mechanism of carbon fiber on cementitious materials can be divided into three aspects. First, the removal or fracture of carbon fiber can absorb energy to improve mechanical properties. Second, hydration products can be tightly bonded to carbon fiber, indicating good adhesion between carbon fiber and cement slurry. Third, carbon fiber can inhibit crack growth.

Figure 5 shows the flexural strength of foam concrete with composite admixture.

As depicted in Figure 5, adding carbon fiber and graphite significantly enhances the flexural strength. The flexural strengths of group C2S1 at 3d and 28d are 4.1 MPa and 4.3 MPa respectively, 262.83% and 249.59% higher than those of Group O at the same age. When the graphite content exceeds 2wt.%, the flexural strength of this group declines, but it is still in the range of 3.4 MPa to 3.7 MPa and higher than the flexural strength of group O. Compared with group C2, the flexural strength values of group C2S1 and group C2S2 mixed with graphite still improve. It shows that the synergistic effect of carbon fiber and graphite can strengthen the flexural strength of specimens, and the specimens with composite admixture has better flexural strength than that mixed with carbon fiber alone when the graphite content is less than 5wt.%. As for the enhancement mechanism, firstly, carbon fiber can absorb energy, adhere to hydration products, and suppress crack growth. Secondly, graphite has the stabilizing effect on foam cement slurry.

3.3 XRD

The XRD patterns of carbon fiber foam concrete at different ages are displayed in Figure 6.

As depicted in Figure 6, the addition of carbon fiber does not make sulfoaluminate cement form new hydration products, that is, carbon fiber does not participate in the hydration reaction. Since carbon fiber has an amorphous structure, there will be no diffraction peaks. The main hydration product of the specimens is ettringite. The dispersion peak at the bottom of the XRD pattern indicates that C-S-H gel and aluminum gel may occur. In Figure 6(a), after 3 days of hydration, the anhydrous calcium sulfoaluminate is consumed completely in the two groups of specimens, and they both have unhydrated anhydrous gypsum and dicalcium silicate. Besides, the diffraction edge of anhydrous gypsum of group C2 is stronger than that of group O which has no carbon fiber. Although carbon fiber has poor water absorption ability, it can serve as an obstacle in cement slurry that restricts the free movement of water molecules at early ages, thus delaying the early hydration process of cement. The XRD pattern of the specimen at 28d is depicted in Figure 6(b). At this point, the hydration reaction is more complete, and the diffraction peak intensity of anhydrite in group C2 drops a lot compared to that at 3d, indicating that the hydration reaction continues at the later age and the diffraction peak intensity is weaker than that of group O at the same age. Besides, with the continuous carbonation of cement, the diffraction peak intensity of calcium carbonate of both groups increase compared to those at 3d.

Figure 7 shows XRD patterns of carbon fiber-graphite foam concrete at different ages.

As exhibited in Figure 7, the group with added carbon fiber and graphite has the strongest diffraction peak intensity of ettringite (the hydration product). Due to the incorporation of graphite, the characteristic diffraction peak of graphite can be observed at 2θ=26.5°. After 3 days of hydration reaction, the diffraction peak intensity of anhydrite of group C2S1 is weaker than those of group C2 and group O. It reveals that graphite can promote the hydration of sulfoaluminate cement at early stages. With the short age period, the diffraction peak intensity of calcium carbonate of the three groups is weak at this time. As the hydration reaction continues, Figure 7(b) shows that the diffraction peak intensity of ettringite of group C2S1 at 28d continues to rise compared to that at 3d while the diffraction peak of anhydrite continues to decline, indicating that the hydration reaction continues. Therefore, the hydration of sulfoaluminate cement is enhanced under the combined action of carbon fiber and graphite.
3.4 Pore size distribution

3.4.1 SEM text

In order to clarify the pore size distribution of the prepared specimens in different groups, SEM test is carried out for statistical analysis. Bubble holes are uniformly selected from the test surface of the specimens for measurement and Figures 8–10 show the pore size distribution results.

Figure 8(a) is the SEM image of foam concrete in Group O, and Figure 8(b) shows the corresponding pore size distribution. As displayed in Figure 8(b), most of the bubble holes in group O have a pore size of 0-400 μm, accounting for 86.85%, and there are no holes larger than 800 μm. The maximum and minimum pore diameters are 66 μm and 796 μm respectively, and the average is 260 μm. The SEM images of the specimens after doping with 0.6 wt.% carbon fiber and the corresponding pore size distribution are shown in Figure 9. The pore size of the C2 group is also concentrated within 400 μm as that of the O group, accounting for 83.78%. However, the percentage of pore size within 200 μm is 43.69%, which is greater than that of group O (38.50%). Therefore, the small pore proportion of the foam concrete can be increased by adding carbon fiber. The minimum pore diameter is 52 μm, which is 14 μm lower than that of group O. This is because during incorporating the foam and the slurry, the carbon fibers evenly dispersed in the slurry effectively split the bubble holes, thus decreasing the size of the bubbles and making the distribution uniform. Furthermore, the random distribution of carbon fibers in the cement slurry can provide support to the slurry, so that the foam mixed into it can remain stable during the hardening of the cement slurry.

Figure 10(a) is the SEM image of foam concrete in group C2S1, and Figure 10(b) shows the corresponding pore size distribution. As exhibited in Figure 10(b), the proportion of pores ranging from 0 to 400 μm is 77.83%, which is 5.95% lower than that of group C2. In group C2, most small bubble holes have the size of 0-200 μm, while those in group C2S1 are between 200 and 400 μm. It indicates that adding 2wt.% graphite can make the pore size distribution of carbon fiber specimens shift to the right. The reason may be that with the addition of graphite and carbon fiber, the slurry becomes too thick due to their dual effects on fluidity, making foams easily broken when mixed with foam. This extends the time required for the cement slurry to mix evenly with the foam.

3.4.2 XCT text

The XCT test is performed on the samples of group O, group C2 and group C2S1. The XCT image data processing and results are shown in Figure 11. Figs.11a, 11b, and 11c are the XCT three-dimensional structure diagrams of the group O, the group C2 and the group C2S1, respectively, and the pore structure of the sample is clearly visible. Figs.11d-11f are the corresponding cross-section images, and the pore colors in the images are green, black and tan, respectively. Figure 11g-11i is the pore size distribution of the sample based on XCT.

From the figures 11a-11c, it can be seen that the porosity of the three groups is different, which is 42.62 %, 48.53 % and 33.22 % respectively. Therefore, the incorporation of carbon fiber increases the porosity of foam concrete, while the porosity of group C2S1 mixed with carbon fiber and graphite is the lowest. The pore size distribution of the three groups shown in figure 11g-11i is similar to that of the SEM pore size distribution in section 3.4.1, and the average pore sizes are 271 μm, 263 μm and 291 μm, respectively. The difference between the average pore sizes obtained by the two methods is 11 μm, 6 μm and 1.19 μm, respectively. Indicating that the pore size distribution obtained by the two methods is similar.

3.5 Conductivity

Carbon fiber and graphite are both resistive loss absorbing materials which mainly rely on their electrical conductivity and dielectric constant, and absorb electromagnetic waves by forming a conductive path inside. The conductivity of cement-based materials without conductive fillers is negligible, and its microwave absorbing performance is also poor. There is a percolation threshold for the content of conductive filler in cement-based materials. When the content reaches the threshold, the conductivity of the material is significantly improved. When the content exceeds the threshold, the conductivity does not increase significantly.
and the increase speed gradually slows down to zero[36]. In order to explore the effects of different contents of carbon fiber and graphite on the conductivity of foam concrete and to provide reference for subsequent electromagnetic parameter tests, the resistivity and conductivity of foam concrete are tested and calculated. Figure 12 shows the conductivity and resistivity of carbon fiber foam concrete.

As demonstrated in Figure 12, group O is the least conductive (only 0.00275 S/m). The conductivity of group C1 with 0.3wt.% carbon fiber increases to 0.00353 S/m, which is due to the tunnel conduction effect[37]. At this time, the conductive effect of carbon fiber gradually improves the internal conductive network of the specimen. As the carbon fiber content rises, the resistivity of group C2 drops to 169.73 Ω/m. The conductivity is 0.00590 S/m which is 114.55% higher than that of group O. Since then, the change in carbon fiber content has little effect on the conductivity, and the conductivity of group C3 with 1.2wt.% carbon fiber is 7.29% higher than that of group C2. It can be assumed that the percolation threshold is reached at 0.6 wt.% of carbon fiber doping.

The resistivity and conductivity of carbon fiber-graphite foam concrete are displayed in Figure 13. The conductivity of foam concrete increases slowly as the graphite content increases. The conductivity of groups C2S1, C2S2, and C2S3 rises 122.91%, 135.64%, and 143.64%, respectively, compared with that of group O. Therefore, the change in graphite content has little effect on conductivity during the adding of carbon fiber and graphite. And the percolation threshold is reached for the groups with the two absorbents when the carbon fiber content is 0.6wt.% and the graphite content is 2wt.%. From the above discussion, it is known that the conductivity of group C2 increases by 114.55% compared to that of group O. Therefore, adding 0 to 10wt.% graphite will not significantly increase the resistivity of carbon fiber foam concrete.

3.6 Electromagnetic characteristics

Complex permittivity $\varepsilon$ and complex permeability $\mu$ are two parameters required for studying the absorption properties of materials. Generally, they are expressed by Eq. 3 and Eq. 4. The real parts $\varepsilon'$ and $\mu'$ indicate the degree of polarization or magnetization of the absorbing material under the influence of an electric field or magnetic field. The imaginary parts $\varepsilon''$ and $\mu''$ respectively represent the measurement of the loss caused by rearrangement of the electrical moment or magnetic moment of the absorbing material under the influence of an applied electric field or magnetic field. The larger the two imaginary parts, the greater the dielectric loss and magnetic loss capability of the absorbing material[38].

$$\varepsilon = \varepsilon' - j\varepsilon'' \quad \text{(Eq. 3)}$$
$$\mu = \mu' - j\mu'' \quad \text{(Eq. 4)}$$

Groups O, C2 and C2S1 are selected for the electromagnetic parameter test. The results are demonstrated in Figure 14-15.

The real and imaginary parts of the complex permittivity of different groups are shown in Figure 14. The values of $\varepsilon'$ and $\varepsilon''$ of Group O are both small, with the range of 1.6-2.5 and 0-0.5, respectively. As can be seen from the chemical composition of cement (see Table 1), the tested cement itself contains a small content of the metal oxides $\text{Al}_2\text{O}_3$, $\text{Fe}_2\text{O}_3$, and $\text{MgO}$. Under the influence of an applied electromagnetic field, they will undergo dielectric polarization, bringing the foam concrete with a certain dielectric loss capability which is poor and negligible. For group C2 mixed with 0.6wt.% carbon fiber, the values of $\varepsilon'$ and $\varepsilon''$ are between 5.9-8 and 0.5-2.2, respectively, which are significantly improved compared with those of group O. Besides, the average value of the imaginary parts is about 1.75 in 4-5 GHz frequency band, indicating that the foam concrete has a larger dielectric loss factor (Eq. 5) and a better dielectric loss capability in this frequency band. For group C2S1, the values of $\varepsilon'$ and $\varepsilon''$ range between 7.9-10.9 and 0.9-3.3, respectively, which are higher than those of the other two groups. The average value of the imaginary parts in 2.2-3 GHz band is about 2.75, which is about 1.75 higher than group C2.

(Eq. 5)

Figure 15 shows the real and imaginary parts of the complex permeability of foam concrete. The real part
values of the complex permeability of three groups have little difference at various frequencies, with the range of 0.25-1.4. The imaginary part values of the complex permeability of three groups are between 0 and 0.7, and the two groups mixed with absorbents have higher values in the 0.5-5 GHz band compared to group O. Furthermore, compared with the complex permittivity in Figure 13, carbon fiber and graphite have a relatively poor effect on increasing the values of $\mu'$ and $\mu''$ of foam concrete. This also corresponds to the loss mechanism of carbon fiber and graphite on electromagnetic waves, which is resistance loss rather than magnetic loss.

The loss characteristics of the material can be characterised by the attenuation constant $a$ (Eq. 6), where $f$ is the frequency of the electromagnetic wave and $c$ is the speed of light, and the larger the value, the more the electromagnetic waves tend to dissipate[39,40]. The calculation results are presented in Figure 16.

(Eq. 6)

The attenuation constant values of Group O are low at different frequencies with the maximum value of only 19.23. It indicates that foam concrete without absorbents has poor electromagnetic wave loss capability, corresponding to the previous conductivity test results. For group C2 with the addition of 0.6 wt.% carbon fiber, the attenuation constant value increases with the increasing frequency and the absorption peak appears between 2.5-3.5 GHz with the value of 47.18. At 3.5-5 GHz, the attenuation constant continues to rise and the maximum value is 70.07, increased by 264.38% over that of group O. Group C2S1 has roughly the same change trend of the attenuation constant as group C2, but the absorption peak is earlier and 11.95 higher than that of group C2. The maximum value is 94.6, which is 391.94% higher and 35.01% higher than those of group O and group C2, respectively. As a result, the electromagnetic wave absorption and loss capacities of specimens are improved by adding carbon fiber alone. For Group C2S1, the absorption peak occurs earlier, which widens the bandwidth with the large attenuation constant.

Reflection loss (RL) is a criterion for the electromagnetic wave absorption characteristics of single-layer planar materials, as in equation 7, and a value of less than -10 dB indicates that more than 90% of the electromagnetic wave is absorbed by the material[41]. The results of RL calculations for three sets of specimens from 0 to 10 mm thickness are shown in Figures 17 to 19.

(Eq. 7)

In this equation: $Z_{in}$ -Input impedance of the material
$\mu_r$ -Relative permeability
$\epsilon_r$ -Relative permittivity
$Z_0$ -Wave impedance of free space
$\mu_0$ -Permeability of free space
$\epsilon_0$ -Permittivity of free space
$d$ -Thickness of material

Figure 17(a) shows the 3d mapped surface plot of the reflection loss for Group O at different thicknesses and frequencies, and Figure 17(b) shows the corresponding two-dimensional curve. It can be seen from Figure 17 that the Group O has almost no electromagnetic wave loss capability and the reflection loss value reaches its minimum value of -3.58 dB at a thickness of 10 mm. As can be seen from Figure 18, the electromagnetic wave loss capability of group C2 is significantly higher than that of group O. The reflection loss value decreases with increasing specimen thickness and appears to be less than -10 dB, with effective bandwidths of 0.8 GHz, 1.7 GHz and 1 GHz at thicknesses of 6, 8 and 10 mm, respectively. The reflection loss reaches a minimum value of -38.47 dB at 10 mm thickness, an increase of 34.89 in absolute value compared to group O. This indicates that the addition of carbon fibre has a significant improvement in the electromagnetic wave loss performance of the foam concrete. The reflective loss of the foam concrete with graphite compounding at
different thicknesses is shown in Figure 19, where the value also decreases with increasing thickness, with effective bandwidths of 2.5 GHz, 1.4 GHz and 0.9 GHz at thicknesses of 6, 8 and 10 mm respectively.

4. Conclusion

In this study, carbon fiber and graphite are mixed into foam concrete, and the impact of single carbon fiber and compound graphite on the mechanical strength, hydration process, electrical conductivity and electromagnetic parameters of foam concrete are studied. In addition, the microstructure of foam concrete is characterized by SEM and XCT tests. The results indicate that:

(1) The specimen achieves its maximum compressive strength and flexural strength when the carbon fiber content is 0.3wt.% and 0.6wt.% respectively. The compressive strength decreases after adding graphite, and changing the graphite content has only a small influence on strength. When the graphite content is 2wt%, the flexural strength is greatest.

(2) Carbon fiber serves as an obstacle in the cement slurry to restrict the free movement of early water molecules and delays the hydration process of cement at early stages. Graphite can promote the hydration of sulfoaluminate cement at early stages. The hydration product of group C2S1, ettringite, has the strongest diffraction peak.

(3) The carbon fiber in the slurry can effectively split the foam and increase the pore size ratio within 400 μm in the foam concrete. When graphite is further added, it increases the pore size of carbon fiber specimens, and most of small pores have the size of 200 to 400 μm. The pore size distribution results obtained from XCT tests are similar to those obtained from SEM tests.

(4) At 0.6wt.% of carbon fiber doping, the percolation threshold is reached and the conductivity of the specimen is 0.00590 S/m, increased by 114.55% than that of group O. For the group with the addition of carbon fiber and graphite, the percolation threshold is reached when the carbon fiber content is 0.6wt.% and the graphite content is 2wt.%.

(5) The foam concrete without wave absorbents has poor electromagnetic wave loss capability, minimum reflection loss of only -3.58 dB. After adding 0.6wt.% carbon fiber, the electromagnetic wave loss capability is increased and effective bandwidth with reflection loss less than -10 dB at a thickness of 8 mm reaches 1.7 GHz, representing 35.42% of the tested band. After compounding with graphite, the absorption peak of the foam concrete occurs earlier and the bandwidth with larger attenuation constant is wider. Effective bandwidth with reflection loss of less than -10 dB at a thickness of 6 mm reaches 2.5 GHz, representing 52.08% of the tested frequency band.

5. Acknowledgements

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6. Data availability statement

Data will be made available on request.

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