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Investigation of the electromagnetic characteristics of cement based composites filled with EPS

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Abstract

Due to the electromagnetic transparency of expanded polystyrene (EPS), the cement-based composites filled with EPS beads can be regarded as a type of ''porous'' material. The electromagnetic reflection loss of this porous composite material in the frequency range from 8 to 18 GHz was studied experimentally in this paper. Findings show that the filling of EPS beads can improve the reflection loss of plain cement material greatly and the EPS filling ratio, EPS bead size and sample thickness all have remarkable effects on the electromagnetic wave reflection loss of this porous composite material. With a EPS filling volume concentration of 60% and EPS size of 1 mm, the reflection loss is all higher than −8 dB in 8–18 GHz and the bandwidth for −10 dB reaches 6.2 GHz for a sample with the thickness of 20 mm. This composite material still has a relatively low bulk density and can be handled easily.

Keywords: Electromagnetic characteristics; Cement based composite; EPS

1. Introduction

Due to its special physical and chemical property and complicated interior structure, porous material has been widely used as a type of acoustic wave absorbing material. These materials have many micro slots and continuous pores, and when acoustic wave transmits into these slots or pores, it causes the air filling in these pores to vibrate and so change the sound energy to heat energy, thus causing the sound energy to be absorbed by the porous material [1]. The sound absorbing property of porous material has been extensively studied [2–4]. The development of information science and technology has brought us great convenience, but also an electromagnetic radiation threat to public health. Electromagnetic interference (EMI) preventing is in increasing demand due to the increasing abundance and sensitivity of electronics, particularly radio frequency devices, which tends to interfere with digital devices. EMI preventing is particularly needed for underground vaults containing transformers and other electronics that are relevant to electric power and telecommunication [5,6]. In this sense, it is urgent that EMI prevention be taken on buildings and electromagnetic shielding and wave absorbing chambers be built to prevent EMI on other devices. Cement-based composite material, which has rich resources and good environmental adaptability, is one of the most common structural materials used in engineering constructions. Cement is slightly conductive and its EMI shielding effectiveness and wave absorbing property are poor, but it is a simple and practical method to increase the cement composite's EMI preventing effectiveness by introducing conductive fillings and loadings [7].

There have been many studies on the reflection loss of cement matrix composite materials, and most of the fillers are metal powders [8,9], fibers [10–12] or ferrites [13–18]. The studies of Xiong et al. show that nanometer sized TiO_2 filled cement material can achieve a reflection loss

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of −8 to −16 dB in 8–18 GHz with a TiO_2 mass percent of 5.0 wt.%, but further introduction will make a decrease in reflection loss [8]. Studies on the electromagnetic reflection loss of steel fiber (with the diameter of 0.7–1.0 mm and length 2–8 cm) reinforced concrete show that a 31-mm-thick sample can give a peak value of −9.8 dB in the frequency range 2–18 GHz, but its comprehensive reflection loss is still comparatively lower [10]. Ref. [12] fabricates a kind of wave absorber with fiber reinforced cement material board, and it has two high peak values higher than −15 dB, but only in 2.4–2.5 GHz and 5.15–5.25 GHz, which is very suitable for application to wireless local area networks (LAN). However, most of the fillers have either high price or relatively complicated process technology. Moreover, metal powder has a disadvantage of high density, which makes a lower absorption property with a small introduction; for a better performance, it must be at the expense of an increase of material density when the loading is increased. Studies on ferrite materials all have shown good reflection loss at lower frequency, but ferrite also has the disadvantage of high bulk density and its electromagnetic absorbing performance deteriorates drastically in higher frequency bands [19].

Expanded polystyrene (EPS), which is a stable low density foam and consists of discrete air voids in a polymer matrix, has a series of excellent properties such as low density, high specific strength and low water absorption. It has been used in concrete to produce lightweight concrete or in cement for thermal insulation [20–22]. Besides, EPS has low electromagnetic parameters [23] and it can be used to adjust the parameters of the cement composite. When coated by a layer of cement, the EPS beads can scatter part of the incident wave on its surface, so the EPS filled cement composites can be looked as a kind of "porous" composite materials. In this paper, the electromagnetic characteristics of this "porous" cement composite were studied. It is shown that it has a good electromagnetic reflection loss and a light bulk density, which applies a new sort of filler for cement matrix functional materials and a new field of EPS for electromagnetic application.

2. Experimental

2.1. Materials

The cementitious starting material used in this study was Portland cement of Type P.O 32.5 R, which was produced by Dalian-Onoda Cement Co., Ltd., China. Its specific area and ignition loss are 3300 $cm^2\ g^{-1}$ and 0.6%, respectively. Its oxide composition is given in Table 1. EPS beads, with the average diameters of 1 mm and 3 mm, were produced by Dalian Hongyu Foam Plastics Co., Ltd., China. Some inorganic solvents and high molecular adhesive binder (polyvinyl alcohol, PVA) were also needed in this work.

Table 1
The oxide composition of P.O cement 32.5 R

Components	SiO_2	Al_2O_3	CaO	MgO	SO_3	Fe_2O_3
Wt.%	21.46	5.96	63.7	1.62	2.38	3.24

2.2. Sample preparation

EPS beads have poor affinity with cement matrix, and they have very low densities. When EPS beads are mixed with cement, the EPS beads will float to the surface of the cement paste and so cause segregation. To make homogeneous dispersion of the EPS particles in the cement paste, the EPS beads were first surface pretreated with acetone and then rinsed with PVA solution to make them hydrophilic.

A UJZ-15 mortar mixer was used in this work. The cement and water were first mixed in the mortar mixer for about 10 min. Then the EPS beads were gradually added to the cement paste and mixed for another 10 min to achieve uniform distribution of the beads. After pouring the mixture into oiled moulds with a size of 200 × 200 mm and a thickness of 10, 20 or 30 mm, the moulds were vibrated on a vibration table for 1 min and then smoothed with a float to facilitate compaction and decrease the number of air bubbles. The specimens were demolded after 24 h and then cured for 28 days, with the mean temperature and humidity of 22 °C and 90% RH, respectively. The composition design of each specimen is shown in Table 2.

2.3. Testing method

The electromagnetic absorbing property of the cement-based composite material filled with EPS beads, which is normally expressed in terms of "reflection loss", was tested in an anechoic chamber using the arched testing method [24], with an Agilent 8720B vector network analyzer (VNA). The testing sketch is shown in Fig. 1. Two pairs of dual-ridge horn antennas (Xi'an HengDa Microwave CO., LTD, China) were used, each for the testing frequency range of 8–12 GHz and 12–18 GHz. The VNA was first calibrated before testing, so as to minimize the horn-to-horn coupling to result high measurement accuracy. Then the sample is put on the reflecting plate which was placed on the support structure for reflection loss testing. The horns are placed at a glancing angle relative to the

Table 2
Mix proportion and bulk density of each sample

No.	Filling material (mm)	Volume (%)	Thickness (mm)	Bulk density ($g\ cm^{-3}$)
1#	Nothing	0	20	2.129
2#	EPS 1	40	20	1.487
3#	EPS 1	50	20	1.244
4#	EPS 1	60	20	1.108
5#	EPS 3	50	20	1.113
6#	EPS 3	60	20	1.008
7#	EPS 1	60	30	1.108
8#	EPS 1	60	10	1.108

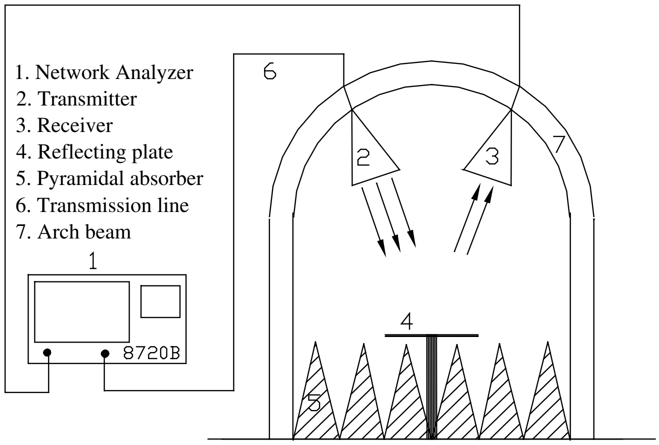

Fig. 1. Sketch of the arch reflecting method.

sample surface, creating a single two-way transmission path with no multiple reflections between the horns and the sample. Then the reading shown on the VNA after the sample was put on the reflecting plate is the reflection loss.

Cement is a kind of complicated hydrated C–S–H mixture, and the free water (pore solution) inside the material has a great influence on its dielectric property [25], thus affecting the electromagnetic absorbing performance of the composite material. To reduce the influence of the free water in the composite material, the samples were first dried at a relatively low temperature (70–80 °C) and then smoothed before testing.

The bulk density of the material mentioned in this paper means the ratio of its weight to its volume, despite the pores inside. And it was calculated from the testing results of the sample volume and its weight according to GB/T 15231-94. For each composition, three samples were tested.

3. Results

3.1. The reflection loss of the porous materials

Fig. 2 indicates the influence of filling EPS volume concentration on the microwave reflection loss of the porous cement composite. It can be seen that the filling of EPS improves the reflection loss of the cement material remarkably. Before EPS introduction, 1# plain cement has only a low reflection loss of about −5 dB, and sample 2# with 40 vol.% EPS filling has only a peak value of −10.42 dB at 9.8 GHz. But sample 4# with the filling of 60 vol.% has a higher reflection loss than sample 2#, 3# and 1# with the same thickness, and the reflection loss increases with the increasing frequency. At 18 GHz, the reflection loss of 4# reaches −15.27 dB and the bandwidth in which the reflection loss is better than −10 dB is as high as 6.2 GHz in the whole bandwidth of 8–18 GHz. The reflection loss of 3# has much fluctuation with several peak values, but its whole performance is still less than that of 4#. As a comparison, the carbon fiber or carbon filament filled

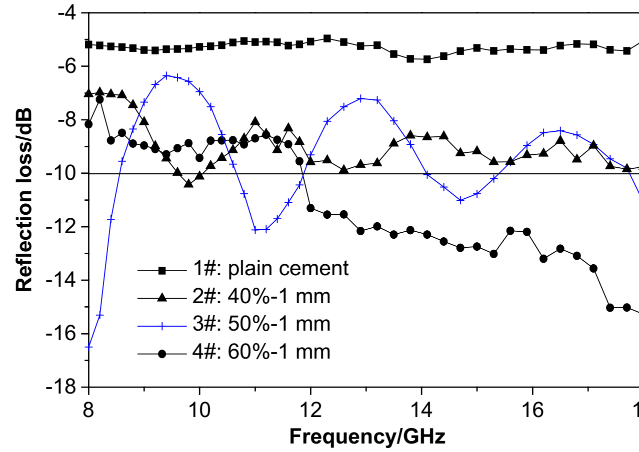

Fig. 2. Effect of EPS filling volume on microwave reflection loss 1#: plain cement paste, 2#: 40 vol.% EPS (Φ1 mm), 3#: 50 vol.% EPS (Φ1 mm), 4#: 60 vol.% EPS (Φ1 mm).

cement composites all have high shielding effectiveness but very low reflection loss owing to their high conductivity [26].

The influence of EPS diameter on the wave reflection loss is shown in Fig. 3, from which it can be seen that as to the samples with the EPS filling volumes of 60 vol.%, sample 6# with the EPS beads size of 3 mm has the reflection loss less than −8 dB, while 4# with the EPS diameter of 1 mm is much better than 6#. As to the samples with the filling ratio of 50 vol.%, 5# has the average reflection loss of −8 to −11 dB except for several peaks, whereas 3# has large fluctuations with several absorbing peak values. At the frequencies lower than 9.5 GHz, the reflection loss of 3# increases drastically and until it reaches a peak value of −16.5 dB at 8 GHz, which is much better than that of 5# with the EPS size of 3 mm.

Fig. 4 shows the effects of sample thickness variation on the reflection loss of the material. The experimental results show that the position and intensity of the reflection peak

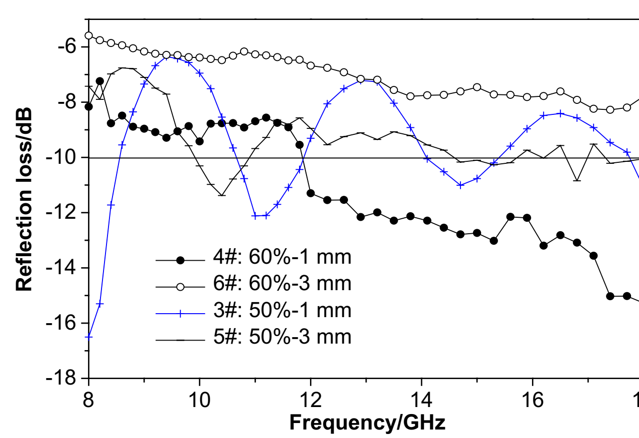

Fig. 3. Effect of EPS bead size on microwave reflection loss 3#: 50 vol.% EPS (Φ1 mm), 4#: 60 vol.% EPS (Φ1 mm) 5#: 50 vol.% EPS (Φ3 mm), 6#: 60 vol.% EPS (Φ3 mm).

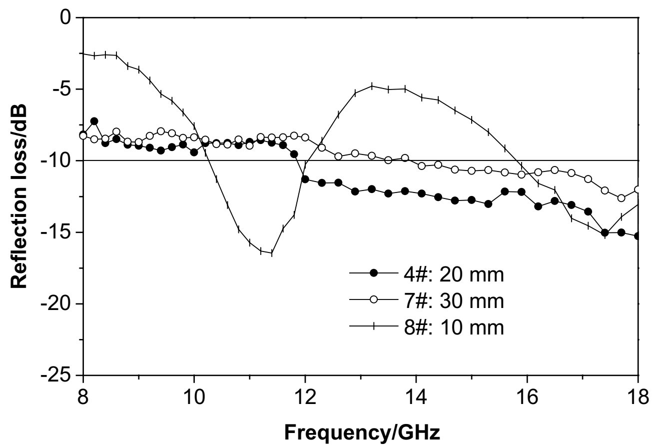

Fig. 4. Effect of thickness on microwave reflection loss 4#: 60 vol.% EPS (20 mm), 7#: 60 vol.% EPS (30 mm), 8#: 60 vol.% EPS (10 mm).

are quite sensitive to the sample thickness. Sample 4# with a thickness of 20 mm has an obviously better reflection loss than 7# with the thickness of 30 mm in the frequency range 8–18 GHz. And for both 4# and 7#, the higher the frequency, the better the reflection losses. The reflection loss of 8# with a thickness of 10 mm has two large peak values, one of which even gets to −16.45 dB, but its whole performance and −10 dB bandwidth are still worse than those of 4#.

3.2. The bulk density of the porous material

For a composite material for building application, bulk density is an important factor to be considered. In this work the bulk density of this porous composite material was studied and the results are also listed in Table 2.

It can be seen from Table 2 that with the increase of EPS filling ratio in the material, the bulk density decreases slowly. The bulk density of the plain cement composite is 2.129 g cm^{-3}, but those of the samples with EPS filling ratio of 40 vol.%, 50 vol.% and 60 vol.% are just 1.487, 1.113–1.244 and 1.008–1.108 g cm^{-3}, respectively. To the samples with a same EPS filling ratio, the smaller the EPS bead size, the higher the bulk density. The comparisons of 4# and 6#, 3# and 5# show that when the EPS size changes from 1 mm to 3 mm, the bulk densities of the samples with a EPS filling of 60 vol.% and 50 vol.% change from 1.108 to 1.008, and 1.244 to 1.113 g cm^{-3}, respectively.

4. Discussion

In contrast to typical polymer matrix, which is electrically insulating and electromagnetically transparent, cement matrix is slightly conductive and has a weak ability of microwave absorption [27]. The attenuation of electromagnetic wave by cement paste, just as that by fly ash [28], can be mostly attributed to the dielectric and magnetic loss of the metal oxide components and some minerals in the cement components. Plain cement has a uniform and relatively compact structure, which causes an impedance mismatching and inhibits the incident wave transmission into the material. EPS has a low permittivity and permeability ($\varepsilon_{r_1} = 1.03, \mu_{r_1} = 1.0$) [29], so it can be used to adjust the microwave transparency and electromagnetic parameters of the cement-based composites. And when coated by a layer of cement, EPS beads can also scatter part of the incident wave on its surface, so cement-based composites filled with EPS can be regarded as a kind of unicellular wave absorbing materials and the EPS beads can be regarded as the "pores". When the incident wave transmits into the "pores", it will be reflected and scattered by the cement coated walls. Moreover, when the incident wave transmits from one "pore" to another, the phase shift will make the incident wave interfere with the reflected wave, which also contributes to the electromagnetic attenuation.

For the EPS filled cement-based composite material, according to literature [30], the attenuation of the incident wave can be expressed approximately as:

$$I = I_0 \exp(-n\sigma_{ex} \cdot x) = I_0 \exp(-n(\sigma_{sc} + \sigma_{ab}) \cdot x) \quad (1)$$

where I_0 and I are the energy intensity at the material surface $x = 0$ and through a thickness x in the material. n is the number of EPS beads in a unit volume of the composite material. σ_{ex}, σ_{sc} and σ_{ab} refer to the extinction, scattering and absorbing cross section, respectively.

For a single-layer plate absorber, its reflection loss with respect to a normally incident plane wave can be expressed as [31]:

$$R = 20 \log \left| \frac{Z-1}{Z+1} \right|, \quad Z = \frac{Z_{in}}{Z_0} = \sqrt{\frac{\mu_r}{\varepsilon_r}} \tanh\left(j\frac{2\pi d}{\lambda_0} \cdot \sqrt{\mu_r \varepsilon_r} \right) \quad (2)$$

where Z is the input impedance normalized by Z_0, d is the thickness of the material and λ_0 is the wavelength of the incident wave in free space.

From Eqs. (1) and (2), it is evident that the microwave reflection loss of this composite material has a direct relationship with the EPS filling ratio, electromagnetic parameters and thickness of the material.

4.1. Influence of EPS on the reflection loss

4.1.1. Influence of EPS filling ratio

From Eq. (1), it can be seen that with the increase of EPS filling, the number of EPS particles n increases, which also leads to the increase of the scattering and multiple scattering between the particles. Moreover the increase of EPS introduction in the cement material improves the impedance matching between the porous material and free space, which makes the incident wave much easier to transmit into the material and attenuated by the wave absorber. So the increase of EPS filler volume can improve the microwave reflection loss of the cement-based porous composite material.

But with the further increase of EPS introduction, the permittivity and permeability of the composite decrease, which weakens the absorbing performance of the composite material. So from this it illuminates that a higher EPS filling ratio does not necessarily mean a higher reflection loss, which also can be seen from the fluctuation in the reflection loss curve of 3# sample shown in Fig. 2.

4.1.2. Influence of EPS beads size

As to the cement-based composite filled with EPS beads, at the same EPS volume content, the decrease of the EPS size is actually the increase of the bead numbers and specific areas, which provides much more opportunities for scattering and multiple scattering of the incident wave. Moreover, the increase of EPS bead numbers also improves the matching between the surface impedance of the material and the impedance of the free space, which leads to a better transmission of the incident wave at the surface of the composite material. So the wave attenuation is increased accordingly.

4.1.3. Influence of sample thickness

As is well known, sample thickness has some effects on the electromagnetic reflection loss of a wave absorbing material, which can also be seen from Eq. (2), and thickness can influence the material's absorbing peak values and bandwidth [32,33]. The increase of thickness is in essence an increase of EPS bead numbers, which leads to the improvement of multiple scattering and multiple reflection times, so the microwave reflection loss can be improved to some degree. However, the change of thickness also changes the impedance matching between the material and the free space, so to each sample with different components, there are one or more optimum thicknesses (matching thickness) [31]. The matching thickness d_m can be expressed as

$$d_m = \frac{c}{2\pi S_0} \tag{3}$$

where c is the wave velocity in free space, and S_0 is the Snoek's value correlates to the electromagnetic parameters of the material [31]. When the sample thickness is beyond the matching thickness in certain frequency band, the microwave reflection loss will not increase but drop gradually, as is shown in Fig. 4.

4.2. Influence of EPS on bulk density

EPS is a kind of stable foam with discrete air voids in a polymer matrix, and it has a very low density [23]. So the introduction of EPS beads into the cement matrix can reduce the bulk density of the cement-based composite material drastically, and the more the EPS filling ratio, the lower the material bulk density. Compared with Φ1 mm EPS, Φ3 mm EPS has more porosity and so has lower density, thus 3 mm EPS filled cement-based composites have lower bulk density than the composites filled with 1 mm EPS beads.

5. Conclusion

Compared with plain cement paste, the electromagnetic reflection loss of cement based porous composite material filled with EPS has been improved greatly. The EPS filling ratio, EPS bead size and sample thickness all have great effects on the reflection loss. With an EPS volume concentration of 60 vol.% and EPS diameter of 1 mm, this composite material with a thickness of 20 mm can give the best reflection loss. Its reflection loss in 8–18 GHz varies from −8.17 dB to −15.27 dB and the higher the frequency, the better the reflection loss. Its high attenuation property may be attributed to the multiple scattering of the EPS particles coated by a layer of cement paste.

The cement-based material filled with EPS has a much lower bulk density than cement paste. With the increase of the EPS filling, the bulk density decreases gradually from 2.129 to 1.008 g cm^{-3}.

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