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Expanded Polystyrene as an Admixture in Cement-Based Composites for Electromagnetic Absorbing

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The electromagnetic characteristics of expanded polystyrene (EPS) filling cement-based composites were studied using arched reflecting method. The findings show that EPS filling ratio and EPS grain size as well as the sample thickness are important to absorbing properties of cement-based composites. The least reflectivity in 8~18 GHz is −15.27 dB and the bandwidth lower than −10 dB is 6.2 GHz, when the EPS filling ratio and thickness of sample are 60 vol.% and 20 mm, respectively, with the EPS diameter of 1 mm. It also indicates that the attenuation of electromagnetic wave can be mainly attributed to the multiple reflection and scattering inside the composite material.

Keywords cement-based composite, electromagnetic absorbing property, EPS

1. Introduction

Electromagnetic interference (EMI) prevention is increasingly demanded due to the increasing sensitivity of electronics, particularly ubiquitous radio frequency devices, which tend to interfere with digital devices. EMI not only influences the normal operation of electronic devices, but also is harmful to people's health. At the present, the electromagnetic radiation emitted from radio broadcast and television station, radio-frequency radiation from electric industry and medical installations, and that from mobile phones have caught people's attention all over the world. In this sense, the development and application of electromagnetic absorbing material with high performance can become more and more important and urgent (Ref 1, 2).

Most of the studies on wave absorbing materials are focused on mobile military targets. There are only few studies on general civilian use, most of which are cement-based composite materials with fine (mortar) or coarse aggregates (concrete). Cement is slightly conducting, but its wave absorbing property is very low, so fillings or loadings are generally introduced to improve the electromagnetic absorbing property of cement-based materials (Ref 1). As to the cement-matrix materials for wave absorbing, there are many factors to be considered, including various physical and chemical reactions between the fillers and the cement matrix, and the electromagnetic properties of the fillers, so as to determine the types and contents of the fillers. Many of the researches have shown that of all the available wave absorbents, the conductive powders, fibers, and magnetic ferrites are suitable to make cement-based wave absorbing materials. Until now, there have been a few published reports on cement-based composite materials with carbon fibers (Ref 3, 4), steel fibers (Ref 5) and ultra-fine particulates (Ref 6) as conductive fillers for microwave absorbing, and their absorbing effectiveness can reach 10–20 dB at the microwave frequency range in which they are tested.

Expanded polystyrene (EPS) has good properties such as low density, high specific strength, low water absorption, and high resistance to acid and alkali and it has got wide use in civil and architectural industries (Ref 7). The wasted EPS beads can easily be incorporated in mortar or concrete as a kind of light aggregate to produce lightweight mortar or concrete with a wide range of densities (Ref 8, 9). EPS filled cement composite has a good property of thermal insulation, besides, it can also be used for EMI prevention indoors (Ref 10). In this work, the wave absorbing property of EPS filled cement composite was studied compared with plain cement. It is shown that the introduction of EPS can improve the microwave attenuation performance. The influences of EPS filling ratio and particle diameter as well as the thicknesses of the composites on the absorbing effectiveness are also discussed, which provide a new kind of wave absorbing component for EMI prevention.

2. Experimental

2.1 Materials

The cementitious starting materials used in this study was Portland cement of Type P·O 32.5R and was produced by Dalian-Onoda Cement Co., Ltd, China. The specific area and ignition loss are 3300 cm^2/g and 0.6%, respectively. Its composition is shown in Table 1. EPS bead, with the diameter of 1 and 3 mm, was produced by Dalian Hongyu Foam Plastics Co., Ltd. Titanate coupling agents NDZ-105 was supplied by Nanjing Shuguang Chemical Group Co., Ltd. High molecular adhesive binder was also needed in this work.

2.2 Sample Preparation

To make homogeneous dispersion of the EPS particles in the cement paste, the EPS was surface pretreated. First the EPS

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Table 1 Composition (wt.%) of P·O cement 32.5R

SiO_2	Al_2O_3	CaO	MgO	SO_3	Fe_2O_3
21.46	5.96	63.7	1.62	2.38	3.24

Table 2 Compositions of experimental design

Sample	Filling material	Composition ratio V/V Filling material	Cement	Thickness, mm
1#	Nothing	0	100%	20
2#	EPS 1 mm	60%	40%	30
3#	EPS 1 mm	60%	40%	20
4#	EPS 1 mm	60%	40%	10
5#	EPS 1 mm	50%	50%	20
6#	EPS 1 mm	40%	60%	20
7#	EPS 3 mm	60%	40%	30
8#	EPS 3 mm	50%	50%	20

beads were rinsed by an inorganic solution to make its surface coarse, then the adhesive binder was diluted with some water and titanate coupling agent solution was subsequently added. After the solution mixture was stirred for about 5 min, the EPS beads were added. Then the EPS particles were heated at a lower temperature for use.

A mortar mixer was used in this work. The cement and water were first mixed in the mortar mixer for about 10 min. Subsequently, the EPS beads were added to the cement paste and mixed for another 10 min. After pouring the mixture into the oiled moulds with the size of 200×200 mm and thickness of 10, 20, and 30 mm, the moulds were vibrated on a vibration table for 1 min to facilitate compaction and decrease the amount of air bubbles and then smoothed with a float. The specimens were demolded after 24 h and then cured at room temperature for 28 days. The composition design of each specimen is shown in Table 2.

2.3 Testing Methods

After curing for 28 days, the specimens were surface smoothed. And to eliminate the influence of free water which exists in the cement composites on the wave absorbing property, all the samples were heated in a lower temperature (85 ~ 90°) before testing.

The electromagnetic absorbing property of EPS filling cement-based materials, which was denoted as reflection loss or reflectivity (R), was tested by the arched reflecting test method in an anechoic chamber (Ref 11). The set-up, as is shown in Fig. 1, was connected to a Hewlett-Packard (HP) 8720B microwave vector network analyzer (VNA) with a dynamic standard attenuation of 95 dB. A calibration kit was first used to calibrate the test system and the specimens were tested in the frequency band ranged 8.0-18.0 GHz.

3. Theory Analysis

3.1 Impedance Matching Analysis

The reflection loss of an absorber has a direct correlation to its input impedance. For a single-layer plate absorber, its reflection loss with respect to a normally incident plane wave can be expressed as

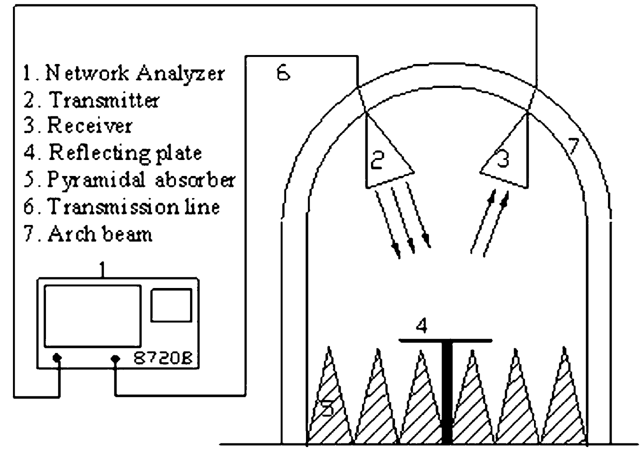

Fig. 1 Sketch of the arched reflecting method

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

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

To make an excellent wave absorption, there are two essential requirements needed. One is that the material should have a good surface impedance matching to make the incident wave transmit into the material; another is that the material should have good wave attenuation performance. In a wave absorbing material, the following formula must be satisfied:

$$T + R + A = 1 \quad \text{(Eq 2)}$$

where T, R and A refer to the transmission coefficient, reflection coefficient and absorption coefficient, respectively (Ref 12). So as to make a good absorption, the reflection must be suppressed first.

In contrast to typical polymer matrix, which is electrically insulating and electromagnetically transparent, cement matrix is slightly conductive and has the ability of microwave absorption (Ref 13). The attenuation of electromagnetic wave by cement paste 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 handicaps the incident wave transmitting into the material. According to the classical effective permittivity theory, the introduction of inclusions with low permittivity can decrease the effective permittivity of the composite (Ref 14). EPS has a low permittivity (Ref 15), so it can be used to adjust the electromagnetic parameters and intrinsic impedance of the cement-based composite. And also it can scatter part of the incident wave on its surface when coated by a layer of cement, so EPS filled cement can be looked as a kind of unicellular wave absorbing material. When the incident wave transmits into the holes, it will be reflected and scattered by the walls of the holes. Moreover, when the incident wave transmits from one hole to another, the phase shift will make the incident wave interfere with the reflected wave, which also attributes to the electromagnetic attenuation.

3.2 Single Particle Scattering And Absorption

Suppose there is an incident wave propagating along the x direction reaches a particle filling composite material, if multiple scattering is negligible, the electromagnetic energy in the material through a thickness of x is (Ref 16)

$$I = I_0 \exp(-n\sigma_{ex}x) = I_0 \exp(-f(\sigma_{ab} + \sigma_{sc})x/\upsilon) \qquad \text{(Eq 3)}$$

in which I_0 and I is the energy intensity at the material surface $x = 0$ and through a thickness x in the material. σ_{ex}, σ_{ab} and σ_{sc} are the extinction cross section (ECS), absorption cross section (ACS) and scattering cross section (SCS) of the particulate, respectively. f and υ refer to the bulk concentration and volume of each particle. n is the number of particles in a unit volume of composite material. So it can be seen that the electromagnetic wave attenuation of a single particle I_{att} includes the absorption attenuation of refracted wave I_{ab} and scattering attenuation of scattered wave I_{sc}. That is to say, $I_{att} = I_{ab} + I_{sc}$ (Ref 17).

The absorption loss of a single particle satisfies exponential attenuation $e^{-\alpha x}$, Viz., $I_{ab} = I_0\, e^{-\alpha x}$, where $\alpha = \sqrt{\pi\mu\sigma f}$ is the attenuation constant. Since both the cement matrix and the EPS particles have very poor electrical conductivity, the absorption loss of EPS filling cement-based composite is very weak and the attenuation can be mainly attributed to the scattering loss.

Cement is a kind of complicated mixture composed of many components, but for the simplification of analysis, taking the cement matrix as one phase system and EPS another phase, then according to (Ref 16, 18),

$$\sigma_{sc} = \frac{k^4\left(|\chi_e|^2 + |\chi_m|^2\right)}{6\pi} = \frac{k^4\left(|\varepsilon_{r1} - 1|^2 + |\mu_{r1} - 1|^2\right)}{6\pi} \qquad \text{(Eq 4)}$$

where χ_e and χ_m are the polarizability and susceptibility, and ε_{r1} and μ_{r1} are the relative effective permittivity and permeability of the cement-based material. So the scattering attenuation can be expressed as following

$$I(x) = I_0 \exp\left(-n\frac{k^4\left(|\varepsilon_{r1} - 1|^2 + |\mu_{r1} - 1|^2\right)}{6\pi}\cdot x\right) \qquad \text{(Eq 5)}$$

where $k = \omega\sqrt{\varepsilon_r\varepsilon_0\mu_r\mu_0}$ is the wave number in cement-matrix composite.

3.3 Multiple Scattering Analysis

For the cement-based composite materials with EPS filling at a high concentration, besides the absorption and scattering loss of single particles and the matrix, the multiple scattering between the particles in the composite must be taken into account. The sketch map is shown in Fig. 2. Since there are so many EPS particles in the composite material, the multiple scattering between the particles are very complicated. On the one hand, the scattering increase the attenuation by the particles; on the other hand they also improve the attenuation by the cement matrix during the scattering.

From Eq (1)-(5) and the above analyses, it is evidently shown that the wave attenuation has a direct relationship with the electromagnetic parameters and thickness of the composite, and to get an optimum wave absorbing performance of a composite material, the thickness and the particle numbers should be considered comprehensively.

4. Results And Discussion

4.1 Influence Of EPS Filling Ratio

It can be seen from Fig. 3 that the introduction of EPS has improved the wave absorbing property of the cement paste obviously, but it is not increased monotonically with the filling volume of EPS beads.

Before EPS introduction, 1# sample of plain cement only has a reflection loss of −5 dB in the whole frequency range, and sample 6# with 40 vol.% EPS filling has only a peak value of −10.42 dB at 9.8 GHz, but sample 3# with 60 vol.% filling of ϕ1 mm EPS has an obviously higher performance than sample 1# and 6# in frequency 8-18 GHz. The bandwidth in which the reflection loss is <−10 dB is as high as 6.2 GHz. The absorbing curve of 5# sample with a filling ratio of 50 vol.% has much fluctuation in the frequency below 11.0 GHz, and it has a peak value of −12.52 dB at 8.0 GHz, but its comprehensive reflection loss is still not as good as that of 3#.

From Eq (3) and (5), it can be seen that the numbers of EPS particles n increase with the increase of filling ratio, which also leads to the increase of the reflection and multiple scattering between the particles. The introduction of EPS into the cement paste improves the impedance matching between the material and free space, which makes the incident wave easier to

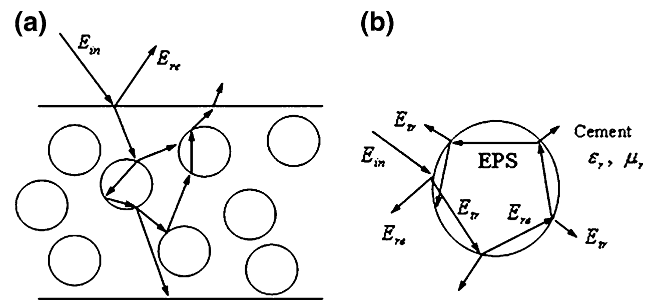

Fig. 2 Sketch of the reflection and multiple scattering wave interior the composite (a) wave transmission interior the cement material plate (b) illustration of the incident wave transmission interior a single EPS particle

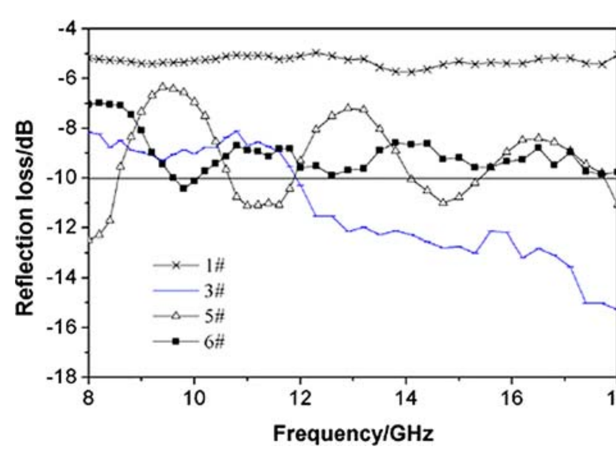

Fig. 3 Effects of EPS filling ratio on reflection loss 1#: plain cement, 3#: 60 vol.% EPS (ϕ1 mm), 5#: 50 vol.% EPS (ϕ1 mm), 6#: 40 vol.% EPS (ϕ1 mm)

transmit into the material and attenuated by the lossy material. So the introduction of EPS can improve the wave absorbing properties of the cement composite. When the EPS filling ratio is low, the impedance matching is not good, so the wave absorbing property is still poor; with the further introduction of EPS particles, the wave transparency property and scattering attenuation are improved, so the wave absorption is also improved gradually.

4.2 Influence Of Sample Thickness

Figure 4 shows the reflection loss of samples 2#, 3#, 4# with the same EPS filling of 60 vol.% and different thickness of 30, 20, and 10 mm, respectively. For comparison, the reflection loss of 1# plain cement paste with the thickness of 20 mm was also tested. It is obvious that sample 3# has a higher reflection loss than that of 2# and 4# with the same filling ratio and also much higher than that of 1# with the same thickness.

As is shown in Fig. 4, the attenuation of 1# is much worse than that of 3# and its reflection loss is only about −5 dB in the whole frequency range. The reflection loss of 2# is better than that of 1#, and it increases with the increase of frequency, but it is still worse than that of 3#. Sample 3# has a peak value of −15.27 dB at 18.0 GHz, and the bandwidth < −10 dB is 6.2 GHz. Sample 4# also has a peak value as high as −22.45 dB at the frequency 11.4 GHz, but its bandwidth < −10 dB is only 1.6 GHz compared with 3#. This peak value may be attributed to the fact that as each microwave absorbing component has certain frequency selectivity and has its own intrinsic absorbing peak in certain frequency, so in a broader frequency band, there will cause one or more peak values.

From Eq (1), it can be obviously seen that thickness has some effects on the electromagnetic wave absorbing property of the material, but the reflection loss is not increasing monotonically with thickness. On the one hand, the increase of thickness in certain degree is in essence the increase of reflecting and scattering times on the surfaces of the EPS beads in the cement matrix, so it can increase the wave attenuation of the incident wave more or less; On the other hand, every wave absorbing material has a matching thickness when its matching frequency is higher than the cutoff frequency. And the matching thickness d_m can be expressed as

$$d_m = \frac{c}{2\pi S_0} \qquad \text{(Eq 6)}$$

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 (Ref 19). When the sample thickness is greater or less than the matching thickness, the wave attenuation property will decrease.

The reflection loss and bandwidth for −10 dB of 3# are better than those of 2# and 4#, especially when the frequency is higher than 12 GHz, so in this work the thickness of 20 mm is superior to 10 and 30 mm.

4.3 Influence Of The EPS Diameter

The EPS beads with the diameter of ϕ3 mm and ϕ1 mm were used in this study to discuss the influence of diameter on the reflection loss of cement-based material filled with EPS.

It is shown in Fig. 5 that the reflection loss of sample 2# is much better than that of 7# with the same thickness and same filling ratio of 60 vol.% EPS of diameter ϕ1 mm and ϕ3 mm, respectively. The peak value of 2# reaches −12.68 dB at 17.7 GHz, and the bandwidth of −10 dB is 3.9 GHz, but the sample 7# only has a peak value of −8.28 dB at 17.4 GHz.

For a single dielectric sphere, it seems like that the smaller the size, the worse the attenuation ability, but for a dielectric filling composite, under the same filling ratio, the reduction of particle size is actually the increase of the particle numbers and the specific surface areas. From Eq (5), it is also evident that the scattering attenuation of the composite material has a close relationship with the particle numbers. Compared with the particulate with 3 mm diameter, ϕ1 mm particle has 27 times quantities and 3 times specific areas, so it has more multiple scattering opportunities. However, EPS particle is a kind of structure with interior discrete pores. The bigger the EPS diameter, the more is the porosity and so the less is the dielectric permittivity. From this sense, cement based composites filled with ϕ3 mm EPS has a lower permittivity and so has better surface impedance matching with the free space.

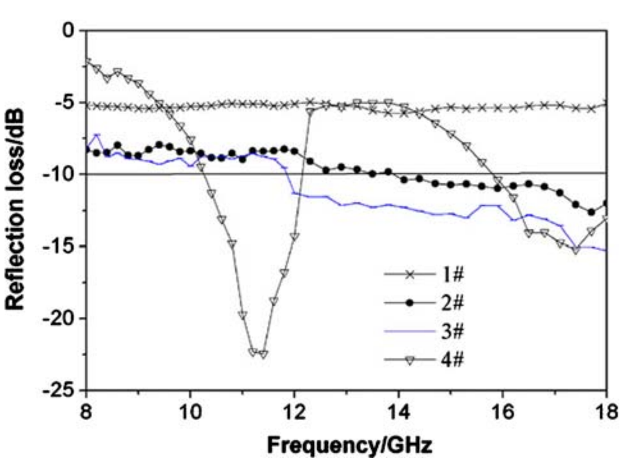

Fig. 4 Effects of sample thickness on reflection loss 1#: cement paste (20 mm), 2#: 60 vol.% EPS (30 mm), 3#: 60 vol.% EPS (20 mm), 4#: 60 vol.% EPS (10 mm)

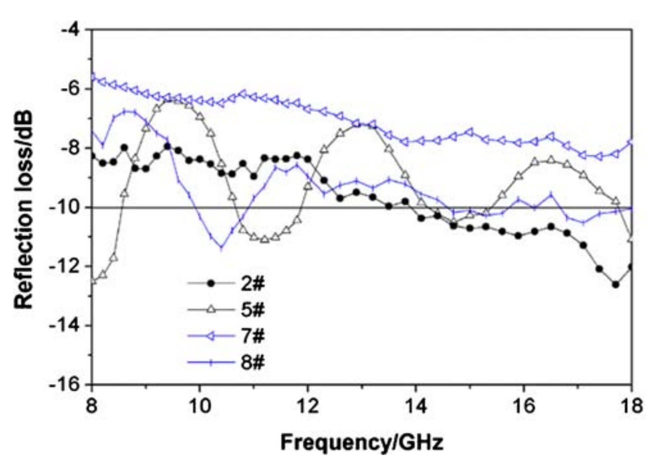

Fig. 5 Effects of EPS diameter on reflection loss 2#: 60 vol.% EPS (ϕ1 mm), 5#: 50 vol.% EPS (ϕ1 mm), 7#: 60 vol.% EPS (ϕ3 mm), 8#: 50 vol.% EPS (ϕ3 mm)

When the EPS filling ratio is 50 vol.%, the wave transparency of the material is not so good, so the wave impedance matching dominates the wave absorbing property. Sample 8# filled with ϕ3 mm EPS has a relatively better impedance matching, so it has a better absorbing property compared with 5#. When the EPS filling ratio reaches 60 vol.%, the composite has good wave impedance matching, and the multiple reflections and scattering attenuation of the EPS particles begin to dominate. Sample 2# with ϕ1 mm EPS has more scattering cross sections and absorption cross sections, so it has better wave absorbing properties.

5. Conclusions

EPS filled cement-based material has much better electromagnetic reflection loss than plain cement paste, and it mainly attenuates electromagnetic wave by the multiple scattering of the particles inside the composite material. The EPS filling ratio, sample thickness and EPS diameter are the main influential factors in this study. The combination of 60 vol.% filling ratio with diameter of 1 mm and a thickness of 20 mm can have better attenuation performance.

References

1. H. Guan, S. Liu, and Y. Duan, et al., Cement based electromagnetic shielding and absorbing building materials, *Cement Concrete Comp*, 2006, **28**(5), p 468–474
2. J. Cao, and D.D.L. Chung, Coke powder as an admixture in cement for electromagnetic interference shielding, *Carbon*, 2003, **41**(12), p 2433–2436
3. X. Fu and D.D.L. Chung, Submicron carbon filament cement matrix composites for electromagnetic interference shielding, *Cement Concrete Res.*, 1996, **26**(10), p 1467–1472
4. D.D.L. Chung, Cement reinforced with short carbon fibers: a multifunctional material, *Composites: Part B.*, 2000, **31**(6-7), p 511–526
5. H. Yang, J. Li, and Q. Ye, et al., Research on absorbing EMW properties of steel fiber concrete, *J. Funct. Mater.*, 2002, **33**(3), p 341–343, in Chinese
6. G. Xiong, M. Deng, and L. Xu, et al., Absorbing electromagnetic wave properties of cement-based composites, *J. Chinese Ceramic Soc.*, 2004, **32**(10), p 1281–1283
7. D. J. Cook. Expanded Polystyrene Concrete, Concrete Technology and Design, Vol 1: New Concrete Materials, by R. N. Swamy, Surry University Press, 1983, p 41-69
8. D.J. Cook, Expanded polystyrene beads as lightweight aggregate for concrete, *Precast Concrete*, 1983, **45**(12), p 691–693
9. B. Chen and J.Y. Liu, Properties of lightweight expanded polystyrene concrete reinforced with steel fiber, *Cement Concrete Res.*, 2004, **34**(7), p 1259–1263
10. Y. Zhao, S. Liu, and H. Guan, Electromagnetic wave absorption properties of cement-based composite filled with expanded polystyrene, *J. Chinese Ceramic Soc.*, 2006, **34**(2), p 225–228
11. A.J. Simmons and W.H. Emerson, An anechoic chamber making use of a new broadband absorbing material, *IRE Int. Convention Rec.*, 1953, **1**(2), p 34–41
12. J. Musil and F. Zacek, *Microwave Measurements of Complex Permittivity by Free Space Methods and Their Applications*, Elsevier, New York, 1986,
13. D.D.L. Chung, Cement-based electronics, *J Electrocera.*, 2001, **6**((1), p 75–88
14. D.J. Bergman, The dielectric constant of a composite materials-A problem in classical physics, *Physics Rep.*, 1978, **43**(9), p 377–407
15. P.C. Bandyopadhyay, T.K. Chaki, and S. Srivastave, et al., Dielectric behavior of polystyrene foam at microwave frequency, *Polymer Eng. Sci.*, 1980, **20**(6), p 441–446
16. C.F. Bohren, and D.R. Huffman, *Absorption and Scattering of Light by Small Particles*, John Wiley and Sons Inc., New York, 1983, p 287–289
17. Y. P. Duan, S. H. Liu, B. Wen, et al., A discrete slab absorber: absorption efficiency and theory analysis. *J. Comp. Mater.*, 2006, in press
18. F. Ge, J. Zhu, L. Chen. Scattering and absorption cross sections of ultrafine particles. Acta Electronica Sinica. (No. 6), 1996, p 82–85
19. Y. Naito and K. Suetake, Application of ferrite to electromagnetic wave absorber and its characteristics, *IEEE Trans. Microwave Theory Tech.*, 1971, **19**(1), p 65–72