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Cement based electromagnetic shielding and absorbing building materials

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Abstract

With more and more severity of electromagnetic environment pollution, the study on building materials that can prevent electromagnetic interference (EMI) has caused great attention. This paper mainly reviews the progress and prospective future of cement-based EMI shielding and wave absorbing building materials.

Keywords: Cement-based materials; EMI shielding; Wave absorbing

1. Introduction

Electromagnetic interference (EMI) preventing is in increasing demand due to the increasing abundance and sensitivity of electronics, particularly radio frequency devices, which tend 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. It is also needed for deterring any electromagnetic forms of spying [1,2]. It is in this sense that the cement based building material which is not only a structural material, but also can have some EMI shielding effectiveness and wave absorbing properties through conductive introductions has caused more and more attention.

Cement material which has rich resource and good environmental adaptability is one of the most common structural materials used in engineering constructions. Cement is slightly conducting, but its EMI shielding effectiveness and wave absorbing property are very low, and it is a simple and practical method to increase the cement materials' EMI preventing effectiveness by introducing conductive fillings and loadings.

There are mainly two methods to prevent and attenuate EMI radiation and leakage, which are shielding and absorbing, and the cement materials that are used to prevent EMI can accordingly be divided into EMI shielding materials and wave absorbing materials.

2. Cement-based EMI shielding materials

So far, extensive researches have been made on shielding and shielding mechanisms, and shielding materials are more extensive and intensive studied compared to absorbing materials. There are, in general, two purposes of a shield namely, to prevent the emissions of the electronics of the product from radiating outside the boundaries of the product and to prevent radiated emissions external to the product's electronics, which may cause electromagnetic interference in the product. So a shield is conceptually a barrier to the transmission of electromagnetic fields [3].

Shielding effectiveness (SE) can be broken into the product of three terms each represents one of the phenomena of reflection loss, absorption loss and multi-reflections. The shielding effectiveness of a shield is defined in decibels (dB) and its magnitude can be written as follows [3]:

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$$\mathrm{SE_{dB}} = 20\lg|E_i/E_t| = R_{dB} + A_{dB} + M_{dB} \quad (1)$$

where E_i and E_t are the electric fields that are incident on and transmitted through the shield, respectively. $R_{dB} = 106 + 10\lg(\sigma_r/f\mu_r)$ is the reflection loss caused by the reflection at the surface of the shield, $A_{dB} = 20\lg(\exp(-t/\delta))$ is the absorption loss of the waves as it proceeds through the shield and $M_{dB} = 20\lg(1 - \exp(-2t/\delta))$ is the additional effects of multiple reflections and transmissions in the interior of the shield. In the above equations, $\delta = \sqrt{1/\pi\mu\sigma f}$ is the skin depth of the shield, a distance into the shield that the incident wave propagates when the wave amplitude decays by a factor of e^{-1} [3].

From the equations mentioned above, it is evident that the shielding effectiveness of a cement based material correlates closely to the electric conductivity and the electromagnetic parameters of the composite. In contrast to a polymer matrix, which is electrically insulating, the cement matrix is slightly conductive and its shielding effectiveness is closely pertinent to its conductivity. Generally there are mainly three kinds of conductive fillers used in cement matrix materials, which are conductive polymers, carbon materials and metal materials. The most commonly used fillings are carbon materials (including graphite, carbon black and carbon fibre) and metal materials (mainly metal powder, metal fibre and metal plate).

2.1. Carbon filling cement materials

As to the cement material that has special performance, the commonly used cementitious starting materials are Portland cement and high alumina cement and the carbon fillers are graphite, carbon black, coke and carbon fibre. They all have comparatively high conductivity and EMI shielding using carbons is mainly by reflection rather than absorption [4].

Graphite is a conductive filler with high conductivity, but its conduction is not very stable, so it is very late when graphite is used as a conductive introduction. Introducing graphite powder into a high alumina cement matrix finds that the graphite's loading threshold is 17.5 vol%. Then shielding effectiveness increases with the increasing of graphite addition. When the volume is increased to 30.0 vol%, a specimen with about 3 mm thickness can give a shielding effectiveness of 10–40 dB in the frequency range 200–1600 MHz [5].

Suspending very fine graphite powder in some water or alcohol, together with a small amount of PVA, colloidal graphite is made. When the water or alcohol evaporates after applying the colloidal graphite to a surface, the graphite particles contact directly with each other. The resulting coating has a very high shielding effectiveness. In a Portland cement matrix composite, colloidal graphite (with the diameter of 0.7–0.8 μm) at 0.92 vol% with the thickness of about 4.4 mm gives a shielding effectiveness of 22.3 dB at 1.0 GHz and 25.6 dB at 1.5 GHz, respectively. Using polyester as the base material and colloidal graphite and PVA binder as the coating, when the coating is 0.3–0.4 mm thick, it can have a shielding effectiveness of 11.2 dB at the frequency of 1.0 GHz [6]. Colloidal graphite conventionally uses submicron graphite particles, but when it is combined with 0.1 μm diameter carbon filaments, its EMI shielding effectiveness can be increased greatly. Studies have shown that the addition of 30 wt.% carbon filaments to commercial graphite colloidal gives a shielding effectiveness as high as 19.8 dB at 1.0 GHz [7].

In the carbon materials, there is a very special kind of graphite, which is called flexible graphite. It is a flexible sheet made by compressing a collection of exfoliated graphite flakes without a binder. Due to the absence of binder, flexible graphite is essentially a kind of pure graphite with a great specific surface area and a high electric conductivity. It is also resilient and impermeable to fluids, so it can be used as a gasket material for special environments [8–10]. Because of its very high specific surface area and electric conductivity, it has a very high skin depth of 44 μm at 1.0–2.0 GHz. Studies show that flexible graphite with 0.79 mm and 3.1 mm thickness can have an EMI shielding effectiveness as high as 101.9 dB and 129.4 dB, which are even higher than copper and nickel with the same thickness of 3.1 mm (100.6 dB and 85.8 dB). Its high EMI shielding effectiveness is attributed mainly to its large specific surface area (15 m^2/g) and high skin depth (44 μm) [11,12].

Coke is usually used as an electrode material for the production of aluminum and a sorbent for bitumen and naphtha, and it is also a raw material for making graphite and steel. Its electric conductivity is not so good as graphite and carbon black, but it is much less expensive, and due to its lower crystallinity, it is less prone to shear and thus superior in mechanical strength. Studies have shown that it is also good conductive filler in cement matrix composite. For the cement composite filled with 9.18 vol% coke powder with the granularity of 200 mesh, a sample with a 4.8 mm thickness can give a shielding effectiveness of 49–51 dB at the frequency 1.0–1.5 GHz [2], which is even higher than that of carbon filaments at 1.02 vol% [13–15].

In order for a conductive filler to be highly effective for shielding, it preferably should have a small unit size, a high conductivity and a high aspect ratio. As to improving the conductive ability and shielding effectiveness of cement matrix composites, carbon fibres are more effective than particles such as carbon black and coke due to their large aspect ratio, which can help to make more conductive networks through intercalating [16–18]. With the decrease in carbon fibre cost and the increase of demand for cement based composites with high structure and multi-function, carbon fibre cement matrix composites are gaining in importance quite rapidly.

In the carbon fibre reinforced cement based composites, the carbon fibre with a diameter of more than 0.1 μm is often called fibre, whereas that with the diameter less than 0.1 μm is often called carbon filament. Due to its higher aspect ratio, carbon filament is superior to carbon fibre in shielding [19,20]. Taking Portland cement as the starting material, along with a small amount of silica fume and methylcellulose, an introduction of 0.50 vol% carbon filament can give a shielding effectiveness of 28.7–30.2 dB for a 4.1-mm-thick sample at the frequency range 1.0–2.0 GHz. In the same volume loading, it is obviously advantageous over carbon fibre filled cement composites [21]. Due to its high radio wave reflection and compressive strength, carbon filament reinforced cement composite material can be used for lateral guidance in automatic highways [13–15].

When the carbon materials are used as the conductive fillers, it is necessary that the fillers be well dispersed, so it often needs to introduce some dispersants. Dispersants are not conductive themselves, but their introduction can obviously improve the dispersion degree of conductive fillers so as to help make more efficient conductive networks. Among the various types of dispersants, styrene butadiene latex and silica fume are the most common for use in cement based composites. Moreover due to the weak strength between the carbon fibre and cement matrix, the introduction of latex, silica fume or methylcellulose can improve the bond between the fibre and matrix, thereby improving the mechanical properties of the cement composites [22,23]. A surface pretreatment of carbon fibre or treating silica fume with silane can improve the bond strength between carbon fibre and the cement matrix and the dispersion degree of conductive fillers, thereby increase the shielding effectiveness of the composites [24–26].

2.2. Metal filling cement composites

Metal based fillers, which are used in cement matrix composites, include metal powder, metal fibre and metal alloys.

Due to their high conductivity, silver, copper and nickel powders have been used for a long time as conductive components in polymers. Silver has a very good conductivity but silver is a type of noble metal and is only used in special occasions. Copper also has a good conductivity and it is much cheaper than silver but it is prone to be oxidized. Nickel is relatively stable and resistant to corrosion but nickel powder has a much lower conductivity than copper and silver. So it has greatly restricted application to cement materials as conductive fillers.

One Japanese Glass Company has developed a kind of shielding glass whose inner side is plated with a strong conductive metal coating and it can reduce the incident electromagnetic intensity to less than one thousandth [27]. Portland cement–lead paste has been studied as shielding materials for gamma radiation emitted from ^{137}Cs-γ-source. Its attenuation coefficient was calculated using NaI (Tl) detector in a gamma spectrometer. The findings show that the attenuation coefficient μ increases as the weight percentage of the lead in the sample increases to 5 wt.% and the curing time to 15 days. A decrease in μ value is observed afterwards. When the curing time increases to 28 days, μ gives another peak value of about 0.25. It is also shown that the total gamma shielding property increases with both the increase of the shield thickness along the direction parallel to the beam direction, and with the increase of the curing process [28]. When the plain cement paste is cured at 100% relative humidity for 24 h and hydrothermally autoclaved at a pressure of 8 atm of saturated steam for 12 h, it can also obtain the attenuation coefficient of 0.25. Also the use of 5% silica fume can reduce the time of autoclaving from 12 h to 6 h [29].

Metal powder has a disadvantage of high density, which makes a lower shielding effectiveness with a small introduction and both an increase of density and a decrease of mechanical strength of the composite material when the loading is increased. By contrast, metal fibre has a high aspect ratio and is liable to be intercalated. So in the same filling with metal powder, metal fibre is more prone to form conductive network; herewith it can provide a better shielding effect with a less loading compared to metal powder. Metal fibre has got a more and more popular application in cement matrix composites as fillers. Only a few studies have been undertaken on metal fibre filled cement matrix shielding materials, and most of the researches are focused on fibre reinforced concretes, which include the effects of concrete structure and the steel bar distribution configurations on the shielding effectiveness of the concrete wall and shielding calculation with finite difference time domain (FDTD) methods.

Chung et al. have studied the magnetic shielding effectiveness of steel paper clips (with a diameter of 0.79 mm and length 31.8 mm) filled cement pastes, which show that paper clips at 5 vol% can provide a magnetic shielding as high as that of a steel mesh with the diameter of 0.6 mm [30]. The paper clips were not continuous, but their intertwining tendency allowed the continuity required for magnetic shielding. Shielding rooms have been composed with reinforcement mesh to provide shielding effectiveness for electromagnetic pulse. For the peak value of plane wave electromagnetic pulse, shielding effectiveness can reach 20–40 dB. It also shows that the shielding effectiveness is closely related to the size of the reinforcement mesh. The thinner the reinforced bar and finer the mesh, the better the shielding effectiveness [31–35].

The proliferation of cellular communication systems in and around man-made structures has resulted in a growing need to determine the shielding properties of various materials commonly used in buildings. This will be useful in two major branches of applications, namely radio base station planning and the effect of exposure to very near radiation sources inside buildings. Most researchers have made many simulations and calculations of the influences of reinforced concrete wall structures and shapes and steel bar distribution configurations on shielding effectiveness with FDTD method. It is shown that at the lowest frequencies, the transmitted signal is attenuated mainly by the rebar structure. As the frequency increases, the effects of the wall become more and more pronounced and result in a larger transmission coefficient. The peak values of the transmission and reflection coefficients start to depend on the complicated interactions between the rebar geometry, the concrete wall thickness and electrical properties. The effects of reinforced wall on the signal attenuation depend on the particular wall structure, electrical properties and incident frequencies. And any changes in these variables can significantly alter the reflection and transmission coefficients [36–38].

3. Cement based wave absorbing materials

EMI shielding is essentially to form an effective enclosed area with high conductive materials, in which the external electromagnetic radiation cannot penetrate and internal radiation cannot be easily leaked out. But shielding cannot eliminate or weaken EMI radiation, and moreover the reflected wave may interact with the incident wave, which causes disturbance to other units or devices. Only by using electromagnetic wave absorbing materials and transferring the electromagnetic energy to other forms can the EMI radiation be attenuated to the furthest extent [39–41].

The electromagnetic absorbing effectiveness of a wave absorbing material is denoted with the reflectivity R, which is expressed as $R = 20\lg|E_r/E_i|$ (dB), where E_i and E_r refer to the electric field strength of the incident and reflected electromagnetic wave, respectively. A reflectivity of −15 to −20 dB is very good for a plate absorber for civil use and it means that the incident electromagnetic wave has been reduced by 82–90%.

According to the wave absorption mechanism, traditional wave absorbers can be divided into three types as electric loss, magnetic loss and dielectric loss materials [42–46]. Carbon materials and conductive polymers are electric attenuation absorbents, which have higher electric loss tangent ($\tan\delta_e$) and the electromagnetic energy is mainly attenuated as a resistor. Ferrites and fine powders are magnetic loss absorbents, which have higher magnetic loss tangent ($\tan\delta_m$), and attenuate and absorb electromagnetic energy by polarization mechanisms such as hysteresis loss and magnetic domain resonance. Metal fibre and many ceramic materials such as barium titanate belong to dielectric loss absorbents, which mainly attenuate electromagnetic energy by electronic and ionic polarization.

As to the cement matrix wave absorbing materials, there are many factors to be considered, such as various physical and chemical reactions between the admixtures and the cement matrix, and the electromagnetic properties of the mixtures, so as to determine the types and contents of the filling admixtures. Taking the economy, practicability and the effects on the other properties of the composite material into account, of all the available wave absorbents, the conductive powders, fibres and magnetic ferrites are suitable to make cement based wave absorbing materials [47,48].

Japan has made great efforts on wave absorbing cement materials and has made great progress. In 1992, Nippon Paint Co. Ltd. started the development of a radio wave absorptive material called BMDM (building material to depress multi-path) using ferrite powder and gypsum board. This kind of material has excellent building material characteristics, one of which is that its weight can be handled by an individual worker without difficulty and it also has good fireproof ability [49]. Russian Concrete Research Institute has developed a kind of conductive cement material, which has excellent absorption performance and low reflection coefficient, and moreover it can reduce the EMI defense cost by 99%.

3.1. Carbon filling cement materials

In the field of cement matrix wave absorbing materials, studies on carbon based composites are very few. Most of the absorbing components are metal fibres and ferrites. Ferrite has excellent absorptive abilities at lower frequencies and can widen the frequency band when combined with other absorbents. As for mechanical strength, the ferrite-cement material can keep such a high strength to meet the demands of ordinary building construction as long as the granularity and the weight ratio to cement are controlled [50].

Using the silicon dioxide and nanometre sized carbon black (CB) N234 as the starting materials and with the help of cohesive binder, we have developed a kind of wave absorbing material which can be used at the floor of an anechoic chamber. A 200 × 200 mm sample with a thickness of 10 mm and the CB volume fraction of 3.0 vol% to that of the silicon dioxide can give a absorptive performance of 6–8 dB at the frequency range 2–8 GHz. The combination with another absorbent can increase the absorbing effectiveness to 15 dB, which is shown in Fig. 1. The physical properties and TEM micrograph of the carbon black N234 are shown in Table 1 and Fig. 2.

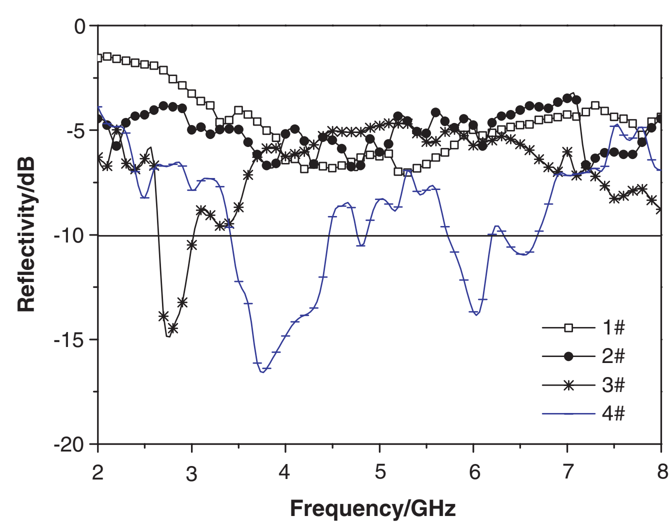

Fig. 1. The absorbing performance of carbon black N234 filling SiO_2 composite materials. 1#: 1.5 vol% CB, 2#: 3.0 vol% CB, 3#: 6.0 vol% CB, 4#: combined wave absorber.

Table 1
Some physical parameters of carbon black N234

DBP[a] absorption number (ml/g)	1.25 ± 5
Iodine absorption (g/kg)	120 ± 5
CTAB[b] surface area (m^2/g)	114–124
Nitrogen surface area (m^2/g)	125 ± 5
Ignition loss (%)	⩽2.5
Ash content (%)	⩽0.5

[a] DBP—Dibutyl phthalate.
[b] CTAB—Cetyl trimethyl ammonium bromide.

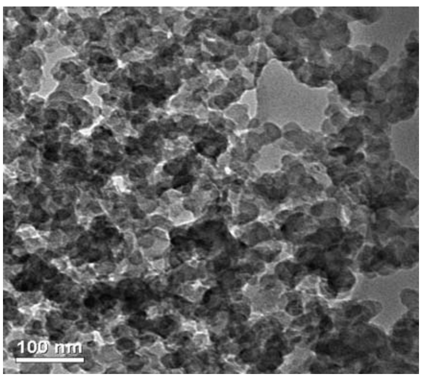

Fig. 2. TEM micrograph of carbon black.

From Fig. 1 it is evident that with the addition of the second wave absorber, the absorbing property increases obviously and there raises two peak values. On the one hand, the adding of the second absorbing component (which has a lower electric conductivity than carbon black) decreases the whole conductivity of the material, therefore the impedance matching between the material surface and the free space is improved, so the reflection decreased and the microwave absorbing ability increased accordingly.

On the other hand, when the electromagnetic wave is incident on the surface of the composite, it can penetrate into the material easier and reflected by the backed surface after the introducing of the second component, then the wave reflected from the front and back surface interferes with each other and cause the absorbing peak values.

3.2. Metal filling cement materials

Most of the metal based absorbents used in cement matrix composites are steel fibres and ferrites, for which Japanese researchers have made many studies.

One Japanese institute has successfully introduced ferrite tiles, steel mesh into the fibre reinforced concrete board or other decoration materials to fabricate a kind of wave absorbing material, which can be applied to a building as an absorptive curtain wall. Adding steel fibres to a powdery glass cullet, they have also made a wave absorbing upholstering material, which gives an absorbing effectiveness of 8 dB at the frequency 2.45 GHz and can also depress the multiple reflections in a room.

Most of the fibres used in wave absorbing materials have a diameter of several microns and so the cost is usually high. Whereas in building construction, steel fibre with a millimetre diameter has stronger bond strength with cement matrix, and both the fibre and cement can bear loads, which obviously increases the strength of the cement composites. Studies on the wave absorbing property of steel fibre (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 and the frequency bandwidth of 15.28 GHz for 4 dB. It also shows that both the peak and the band width increase with the aspect ratio of the steel fibre. But the fibre aspect ratio has a threshold and when it is out of the critic value the absorbing effectiveness will decrease drastically with the increase of the aspect ratio [51].

Using cement and ferrite or fibre cloth as the materials, Japan has fabricated a kind of curtain wall. It can absorb 90% of the incident electromagnetic waves and give an absorbing effectiveness of 20–30 dB in the frequency range 100–200 MHz. It also has a light weight and a shockproof ability, and has been successfully used in several buildings in Tokyo and Hiroshima [52]. One Japanese Construction Research Institute has developed a concrete curtain wall material with Mn–Zn and Mg–Zn ferrite, which can give an absorption effectiveness of 5 dB in the frequency 90–450 MHz [53]. Using ferrite and aramid fibre as the absorbing components, mixing with steel fibre or metal mesh can also give an absorbing performance of about 14 dB at the frequency of 80–220 MHz [54,55].

Ferrite is a good kind of wave absorbing component, especially in lower frequencies, but its cost is also higher. In view of decreasing cost and using local materials, magnetite sand is also a practicable wave absorbent. A 180×180 mm sample with a thickness of 30 mm can give an absorption performance of 7–9 dB in the frequency range 75–100 GHz [56–58]. Moreover, magnetite sand has a relatively rich resource and lower cost, which may make it a practical admixture for cement matrix functional composites.

4. New types of fillings

With the rapid development of nano-science, nanostructure wave absorbing materials have caused more and more attention. Nano-sized particles are much less than the incident wavelength, so it can greatly reduce the reflection from the surface, which makes better impedance matching. Moreover, nanometre particles have much large specific surface areas than normal particulates, therefore, when the electromagnetic wave penetrates the material, there will be more particles to be polarized to cause magnetic domain resonance and eddy loss, and thus lead to better wave absorbing performance [59–61].

Hollow microsphere is a new kind of multi-functional material. It is the fine, light and centre hollowed parts of the fly ash generated from coal combustion by electrical utilities with the main component of oxides of silicon, aluminum and iron. After it is under surface treatment, it can be used for preparation of EMI shielding or wave absorbing materials [62–65].

Fly ash, which has some similar physical and chemical properties as silica fume, has a small granularity of 3–300 μm and a small specific gravity, and can be used as a good dispersant. Using Portland cement as the base material and fly ash as the admixture, the fabricated composite can be used as an EMI shielding material. Studies show that a 4.3-mm-thick sample can have a shielding effectiveness of 4 dB in the frequency range 1.0–1.5 GHz. It is also shown that the shielding effectiveness is increased monotonically by increasing the fly ash proportion, while the attenuation upon reflection is decreased slightly and monotonically, which means that the fly ash enhances the shielding through improving the reflectivity. Although silica fume decreases the resistivity of cement more than fly ash, it is less effective than fly ash for shielding. This suggests that the shielding provided by the use of fly ash is not only due to reflection but is also due to absorption, which is attributed to the existence of Fe_2O_3 in the fly ash. It is also believed that the pozzolanic nature of silica fume and fly ash makes the large area of interface between the silica fume or fly ash and cement matrix contribute to the conductivity [66].

Every year, millions of tons of fly ash are generated all over the world and have caused great pollution. Through pretreating, they can be used as admixtures and applied to the cement matrix building materials for providing shielding and wave absorbing functions, which will be a practicable and economical way to dispose of them.

There are also many other conductive fillers, such as nickel plated carbon fibres [67], nickel coated mica [68], conductive papers [69–71] and magnetic woods [72,73]. However, these fillings are not only high in cost, but complicated in processing, so they are not commonly used in cement matrix composites.

5. Conclusion

The development and application of cement matrix materials with EMI shielding and absorbing properties to attenuate electromagnetic radiations have been more and more urgently required with the deteriorated electromagnetic environments. This emerging technology provides a new direction for the use of cement matrix materials for electromagnetic functions.

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