

Piecewise Empirical Model for Shielding Effectiveness Prediction of Graphite-Cement Powder Mixture

See Khee Yee^{1, a} and Mohd Zarar bin Mohd Jenu^{2, b}

^{1,2}Research Center for Applied Electromagnetic

³Universiti Tun Hussein Onn Malaysia

^askyee@uthm.edu.my, ^bzarar@uthm.edu.my

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Abstract. The addition of conductive fillers into insulating matrix will improve its shielding effectiveness (SE). In this work, the graphite fine powder is added into the cement powder for SE enhancement. The SE of the mixture can be calculated analytically but this requires dielectric properties of the mixture. When there are changes of mixture proportion, a new dielectric measurement must be repeated. This is inconvenient especially to the civil engineers who are more concern on the relationship between the percentages of additive to the resultant SE. A piecewise empirical model which is working in between 100 MHz to 2000 MHz is proposed in this work. The model able to estimate the SE of the graphite-cement mixture with thickness of 1 cm. Different graphite-cement samples with different percentage of graphite fine powder are prepared and dielectric measurements are executed to obtain their dielectric properties. Their SE are analytical calculated based on the measured properties and it is used to establish the model for SE prediction. Based on this model the users able to predict the resultant SE of the mixture and hence proposed the best graphite-cement proportion to fulfill the cost effective requirement.

Introduction

Environmental exposure to man-made electromagnetic fields has been steadily increasing as the result of growing electricity demand in executing complex task. As the result, the society are exposed to complex mix of weak electric and magnetic fields, both at home and at work, from the generation and transmission of electricity, domestic appliances and industrial equipment, to telecommunications and broadcasting. This electromagnetic (EM) environment has created a new form of pollution known as electromagnetic pollution or electromagnetic interference (EMI) [1]. EMI consists of many unwanted radiated signals which can cause unacceptable degradation of system or equipment performance. Therefore it is important to provide shielding protection to the electrical and electronic devices [2].

The conventional shielding technique is by building a shielding room or Faraday cage which is made of metallic material [2]. However it is bulky, expensive and provides protection for certain area inside a building. The current researches start to focus on improving the shielding capability of the building itself since it is more practical and it provides more protection not only to electrical and electronic devices but also human inside the building.

A lot of researches related to the shielding effectiveness (SE) of building material had been carried out [3-7]. The inherent shielding provided by building material is very limited. It is reported that a concrete wall with thickness 300 mm and 5.5 percent of moisture content able to provide 3-10 dB of shielding in between 0.03 GHz to 1 GHz [3]. Hence different kinds of shielding and absorbing material in the form powder, fibre, filament and so on are added to the building material to further enhance its SE [7]. Most of the researches only focus on the comparison of SE before and after the addition of additives, and they showed the effects of additives with different percentage to the SE of building material. However, there is no rigorous guideline provided to indicate the correlation between the percentages of the additives to the SE of building material.

This work propose a simple model which able to show the relationship between the percentages of graphite fine powder to the SE of graphite-cement mixture in the frequency range between 100 MHz to 2 GHz. The thickness of the material is fixed at 1cm.

The first section describes briefly the concept of shielding and its analytical calculation. Next, the procedures to prepare different percentages of graphite-cement powder are explained. Dielectric measurements are carried out to disclose the dielectric properties of the samples so that its SE can be calculated analytically. A model is established based on the calculated SE and it is explained in section VI. The new model will be evaluated by using new percentage of graphite-cement mixture.

Concept of Shielding

Shielding effectiveness (SE) is a parameter which is used to indicate the capability of a barrier in attenuating the incoming electromagnetic (EM) wave. It is often expressed by the (1) or (2) where E and H are electric and magnetic fields and the subscripts t and i refer to the transmitted and incident waves. E is measured in volts/m and H in amps/m. It is a function of frequency. Alternatively, the SE can also be expressed by (3) where it is derived as the combination of absorption loss (A_{dB}), reflection loss (R_{dB}) and multiple re-reflection loss (M_{dB}) [2].

$$SE(dB) = 20 \log \left[\frac{E_i}{E_t} \right] \quad (1)$$

$$SE(dB) = 20 \log \left[\frac{H_i}{H_t} \right] \quad (2)$$

$$SE(dB) = A_{dB} + R_{dB} + M_{dB} \quad (3)$$

where

$$A_{dB} = 20 \log |e^{-\gamma d}| \quad (4)$$

$$R_{dB} = 20 \log \left| \frac{(\eta_o + \eta)^2}{4\eta_o \eta} \right| \quad (5)$$

$$M_{dB} = 20 \log \left| 1 - \left(\frac{\eta_o - \eta}{\eta_o + \eta} \right)^2 e^{-\gamma d} \right| \quad (6)$$

$\eta_o = \sqrt{\epsilon_o \mu_o}$ and $\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon'}}$ are the intrinsic impedance of free space and material respectively. μ and ϵ is the permeability and permittivity of the material, $\sigma = \epsilon'' \epsilon_o \omega$ is the conductivity of the material, ω is the angular frequency, $\gamma = \sqrt{j\omega\mu(\sigma + j\omega\epsilon')}$ is the propagation constant and d is the thickness of the material. The SE can be analytical calculated once the permeability, permittivity and conductivity of the material are defined based on dielectric measurement.

Permittivity is a quantity used to describe dielectric properties that influence reflection of EM wave at the interfaces and the attenuation of wave energy within materials. The complex relative permittivity, ϵ^* of a material to that of free space can be expressed as (7). The real part of the complex permittivity, ϵ' is the dielectric constant which represents the energy that able to be stored by the material when it is exposed to electric fields, where the imaginary part, ϵ'' represents the loss factor. It describes the energy absorption and attenuation within the material [8].

$$\epsilon^* = \epsilon' - j\epsilon'' \quad \square \quad \square \quad (7)$$

It is found that the dielectric constant determine the trend of the reflection loss because it plays heavy role in determining the characteristic impedance of the material [9]. The reflection loss is higher at lower frequencies and it depends on the impedance matching between the material and the medium before the EM wave penetrates to the material. For instance, if the EM wave propagates from air to the material, the reflection loss depends on the characteristic impedance of the air (377Ω) and the material itself. If both of the characteristic impedances are comparable, it results in lower reflection loss and vice-verse. When an EM wave is impinging on a metal material from air, it experiences great changes of characteristic impedance (from 377Ω to nearly 0Ω , for perfect conductor) the mismatching results in higher reflection loss.

Absorption loss is a function which greatly relies on the loss factor, permeability and thickness of the material. For a non-magnetic material as in the subject of this research, the absorption loss depends strongly on the loss factor of the material.

Experiments

Cement-graphite Powder Preparation. Graphite fine powder is naturally abundant as well as synthetically prepared inorganic material, which has significant influence on the electrical and thermal conductivity of filled materials. It is frequently used especially for an improvement of electrical conductivity, antistatic properties as well as thermal conductivity of the filled material [10]. Besides that, it is less weight and resistance to corrosion, [11].

In this work, the HmBG graphite fine powder is added to the cement powder as electrical conductive filler to enhance the SE of cement matrix. The cement powder used in this work is Holcim Top Standard Cement, it is portland fly ash cement. It is produced by heating a mixture of limestone and clay in a kiln at about $1450\text{ }^{\circ}\text{C}$, then grinding to a fine powder with a small addition of gypsum.

The weight of the cement powder and graphite fine powder in each of the samples are shown in Table 1. Both of the materials are blended together evenly before they are undergoing the dielectric measurement. The illustrations of the graphite fine powder, cement powder and graphite-cement mixture are shown in Fig. 1.

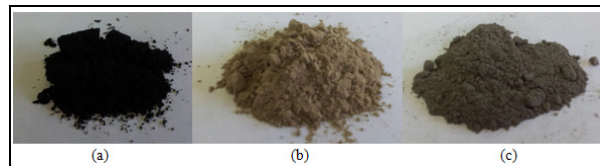


Figure 1: The graphite fine powder (a), cement powder (b) and graphite-cement mixture (c)

Samples	Amount of graphite fine powder (g)	Amount of cement powder (g)
1	0	10
2	0.7	9.3
3	1.1	8.9
4	1.5	8.5
5	1.9	8.1
6	2.3	7.7
7	3	7

Table 1: Samples with Different Amount of Graphite Fine Powder and Cement Powder

Dielectric Measurement. There are various dielectric measurement method, including both time-domain and frequency domain method. The existing systems are mainly based on coaxial probes, free space, transmission/reflection methods using waveguide or coaxial cells and resonance

techniques [12]. The systems to be chosen basically depends on the frequency range of interest, form of material (solid, semi-solid or liquid), the restriction of sample size, destructive testing or non-destructive testing, and so on.



Figure. 2: A pair of APC7 connectors is used for dielectric measurement.

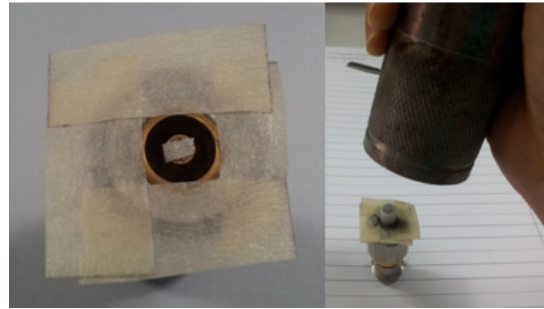


Figure 3: The powder is placed into the connector and compressed with a 6kg of steel block.

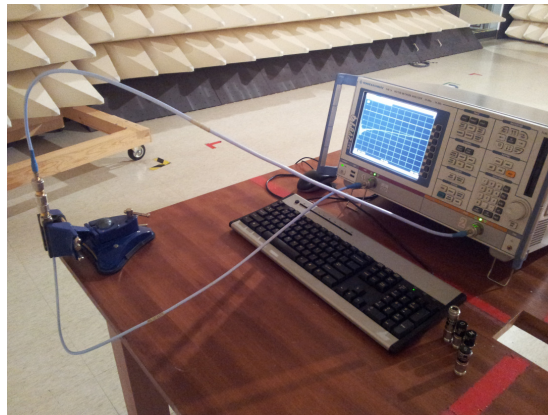


Fig. 4: Dielectric measurement setup

A pair of APC7 connectors as shown in Fig. 2 is used for dielectric measurement in this work. The samples in the form of powder are placed into the slot as shown in Fig. 3 carefully and compressed by using a 6 kg of steel block to ensure the air is eliminated. After that, both APC 7 connector is combined and connected to the network analyzer. The network analyzer will measure its S-parameters. The Nicolson-Ross-Weir (NRW) conversion formulation with specific calibration [12] is used to convert the S-parameters to the dielectric properties (complex relative permittivity) of the composites.

Result and Discussion

Dielectric Constant and Loss Factor. The dielectric properties of the samples are illustrated in Fig 5-7. It is found that the dielectric constant increase gradually as the percentage of the graphite increases. When the graphite is added in small amount, the increment of the dielectric constant is linear throughout the whole frequency range. However as the percentage of the graphite exceed 19 percent (sample 5 onward), the dielectric constant start to behave exponentially.

On the other hand, the loss factor does not experience significant changes when the percentage of graphite is below 15 percent. However when more graphite is added, the changes on the loss factor become obvious especially when the percentage of the graphite reaches 30 percent.

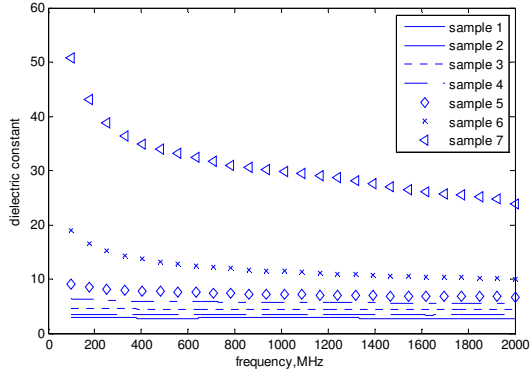


Figure 5: The dielectric constant of the samples

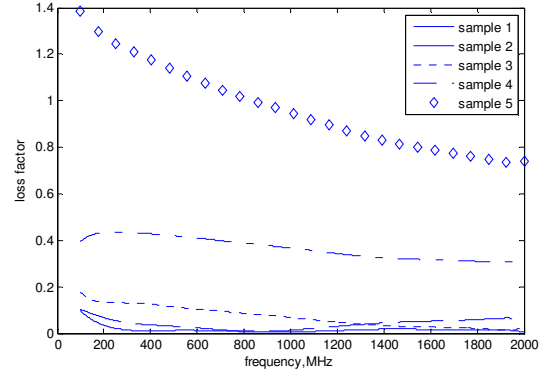


Figure 6: The loss factor of sample 1 to sample 5

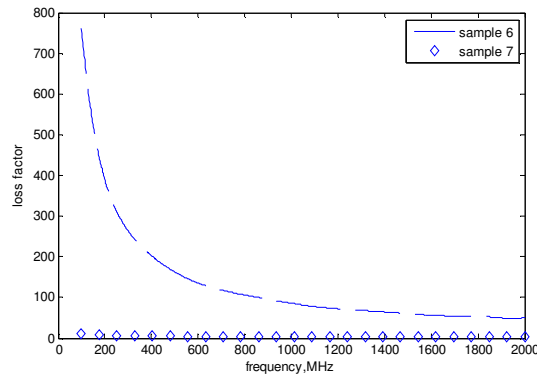


Figure 7: The loss factor of sample 6 to sample 7

Analytical Calculation of SE. The relative permeability of all the samples is unity since the resultant composite are non-magnetic material. Based on the measured dielectric properties in previous section, the SE of all the samples with thickness of 1 cm is calculated based on (3). The results are shown in Fig. 8.

The inherent shielding provided by the cement powder is below 1 dB and it is not adequate to attenuate the incoming EM field. The addition of the graphite increases the SE of the cement powder slowly when the percentage of the graphite is lower. As the percentage of the graphite increases up to 30 percent, significant changes can be observed based on the results.

It is found that, the reflection loss and absorption loss is the main contributors to the SE increment of the graphite-cement mixture. The reflection loss contributes more at lower frequencies whereas the absorption loss contributes more at higher frequencies. When the graphite fine powder is added in small amount, the multiple re-reflection loss is in negative value for samples with lower amount of graphite find powder (15% below).

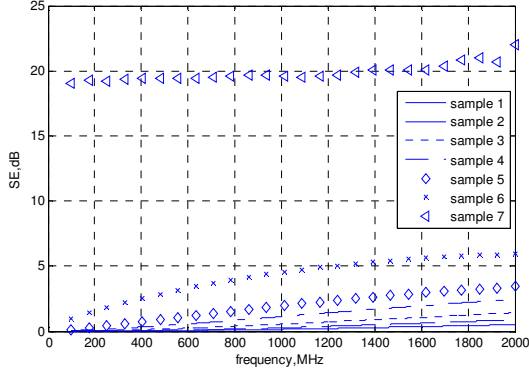


Figure 8: The SE (dB) of all the samples from 100 MHz to 2000 MHz

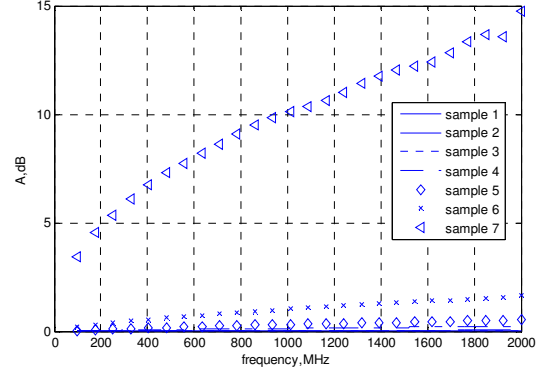


Figure 9: The absorption loss (dB) of all the samples from 100 MHz to 2000 MHz

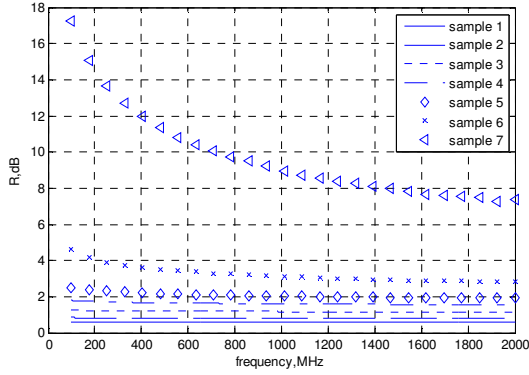


Figure. 10: The reflection loss (dB) of all the samples from 100 MHz to 2000 MHz

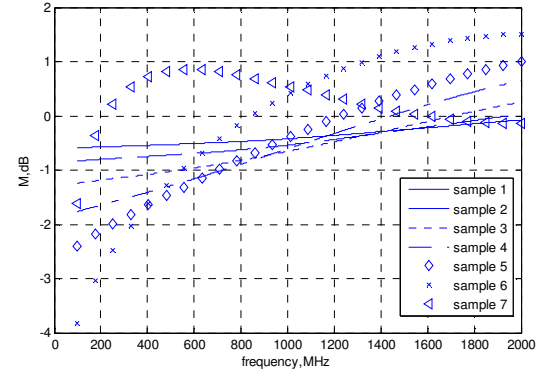


Figure. 11: The multiple re-reflection loss (dB) of all the samples from 100 MHz to 2000 MHz

Shielding Effectiveness Prediction. The analytical technique discussed in section IV can accurately determine the SE of the graphite-cement mixture but it requires the characterization of the dielectric properties of the mixture through dielectric measurement. A new dielectric measurement must be repeated for every change of graphite-cement proportion. This procedure is quite technical especially for civil engineers who are not familiar to the dielectric measurement. They are more concern about the prediction model which able to show the relationship between the percentage of graphite to the resultant SE of graphite-cement mixture.

The relationship of the frequency and percentage to the SE of graphite-cement mixture can be represented by the piecewise function in eq. 8, where f represent the frequency and $\%$ represent the percentage of the graphite in the mixture.

$$SE_{dB} = a \times b^{\%} \quad (8)$$

$$a = \begin{cases} 6.271 \times 10^{-5} f - 0.001177 & 100 \leq f \leq 600 \text{ MHz} \\ 0.0001283 f - 0.04257 & 600 < f \leq 1700 \text{ MHz} \\ 4.96 \times 10^{-5} f + 0.09319 & 1700 < f \leq 2000 \text{ MHz} \end{cases}$$

$$b = \begin{cases} -0.0001406 f + 1.313 & 100 \leq f \leq 600 \text{ MHz} \\ -6.774 \times 10^{-5} f + 1.27 & 600 < f \leq 1300 \text{ MHz} \\ -2.095 \times 10^{-5} f + 1.21 & 1300 < f \leq 2000 \text{ MHz} \end{cases}$$

The results of the model showed good agreement with the analytical calculated results. Fig. 12-15 shows the relationship between the model and the analytical calculated data at selected frequencies. The accuracy of the model can be described using absolute error as shown in (9), where Y represent the analytical calculated results and X represent the predicted results based on the proposed model. The absolute error of the samples with different percentage of graphite is shown in Table II.

$$\text{absolute error} = |Y - X| \quad (9)$$

The table shows that at frequency 1200 MHz, the model gives the smallest absolute error for the SE compared to the other frequencies whereas at 200 MHz it shows the highest. Based on the mean absolute error in Table II, it is believed that the proposed model can be used as a reliable formulation for SE prediction.

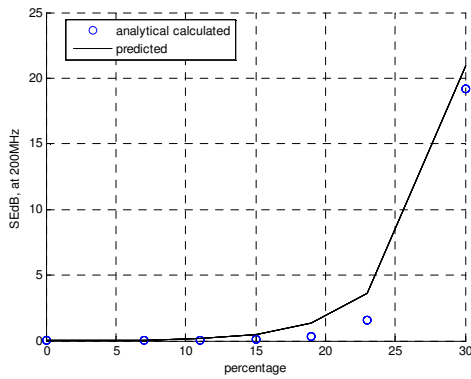


Figure 12: Comparison of analytical calculated and predicted SE at 200 MHz.

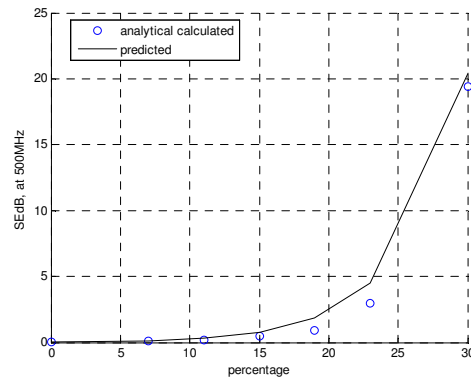


Figure 13: Comparison of analytical calculated and predicted SE at 500 MHz.

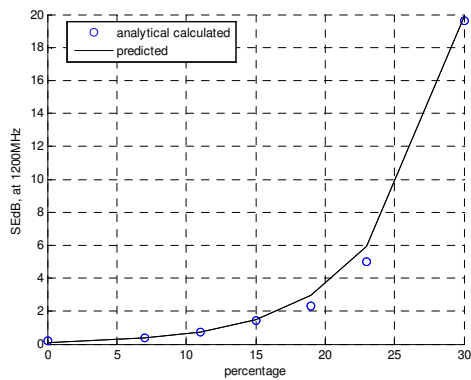


Figure. 14: Comparison of analytical calculated and predicted SE at 1200 MHz.

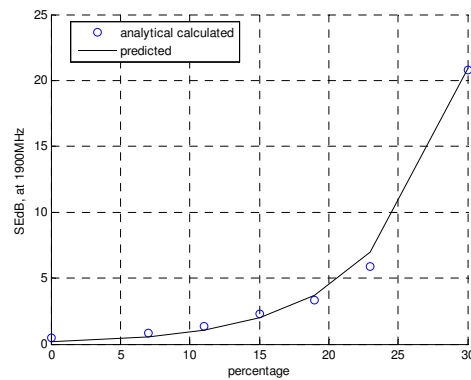


Figure. 15: Comparison of analytical calculated and predicted SE at 1900 MHz.

Percentage of Graphite, %	Frequency, MHz			
	200	500	1200	1900
0	0.0019	0.0125	0.1108	0.2808
7	0.0432	0.0616	0.0081	0.2573

11	0.1293	0.1407	0.0223	0.287
15	0.3597	0.3377	0.0675	0.3484
19	0.999	0.9473	0.6499	0.3955
23	2.0377	1.5171	0.951	1.0771
30	1.7556	1.0062	0.3046	0.1024
Mean	0.7609	0.5747	0.3020	0.3926

Table 2: The Absolute Error Between Predicted Data and Analytical Calculated Data

Hence, two new samples with 13 percent and 26 percent of graphite are prepared in order to evaluate the efficiency of the model. The new samples undergoing similar process as the other samples, their dielectric properties are identified based on the dielectric measurement and their analytical SE are calculated based on (3) The predicted results based on the model and analytical calculated results are tabulated in Table 3.

It is found that for all the frequencies, the absolute error of sample with 26 percent of graphite fine powder is higher compare to those with 13 percent of graphite fine powder. The model proposed in section V is based on the analytical calculated SE where the dielectric properties of the samples are obtained based on dielectric measurement. There are lacks of samples in between 23 percent to 30. Hence the model produces higher error in this percentage range.

Frequency, MHz	13% of graphite			26% of graphite		
	Predicted SE (dB)	Analytical calculated SE (dB)	absolute error	Predicted SE (dB)	Analytical calculated SE (dB)	absolute error
200	0.2957	0.0813	0.2144	7.6912	10.4549	2.7637
500	0.5087	0.2997	0.209	8.5746	11.5555	2.9809
1200	1.054	1.0524	0.0016	9.9733	12.41	2.4367
1900	1.4461	1.8309	0.3848	11.1572	12.4107	1.2535

Table 3: Comparison between predicted SE and analytical calculated SE for 13% and 26% of graphite samples.

Summary

The addition of the graphite fine powder successfully increases the shielding effectiveness of the cement powder. The dielectric measurement indicates the dielectric constant of the samples increase steadily as the percentage of graphite increases and this characteristic is reflected in the reflection loss. The improvement in the loss factor is inferior when the percentage of the graphite is lower than 11 percent. However it experience significant raise when 30 percent of graphite is added into the cement powder. This results in meaningful increment on the absorption loss and also the resultant SE of the graphite-cement mixture. The performance of the proposed model in predicting the SE of graphite-cement mixture is commendable as it produces low absolute error. This model has the best performance when the percentage of graphite is in between 7 to 19 percent and applicable in between 100 MHz to 2000 MHz for a 1cm thick of graphite-cement mixture.

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