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RESEARCH ARTICLE

Multiphase Dielectric Mixing Model for Concrete Mixtures

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ABSTRACT The advancement of high-power microwave technology has indeed brought about the possibility of E-bombs, also known as electromagnetic pulse (EMP) bombs. These weapons emit an electromagnetic pulse that can disable electrical circuitry within a specific radius. As the frequency spectrum becomes more congested with various technologies operating in similar frequency bands, the need for shielding against interference becomes crucial. One promising solution is the use of conductive concrete, which is created by incorporating conductive components into a traditional concrete mixture. This conductive concrete has shown excellent shielding properties and improved electrical characteristics. To assess and quantify its effectiveness, the relative complex permittivity of the concrete mixture needs to be estimated. In this paper, the authors propose a method for estimating the relative complex permittivity of the concrete mixture. This was achieved by measuring the scattering parameters of concrete samples using a rectangular waveguide within the C-band frequency range. The scattering parameters provide valuable information about how electromagnetic waves interact with the concrete. A dielectric mixing model was developed to determine the relative complex permittivity. This model takes into account the volume percentage and the dielectric properties of the individual constituents present in the concrete mixture. By applying this model and obtaining the complex permittivity of the mixture, it becomes possible to calculate the required thickness of the conductive concrete mix needed to achieve the desired levels of electromagnetic attenuation and shielding.

INDEX TERMS Conductive concrete, dielectric constant, dielectric mixing model, electromagnetic shielding, rectangular waveguide, scattering parameters.

I. INTRODUCTION

Conductive concrete is a specialized type of concrete that incorporates electrically conductive materials into the regular concrete mix. This is typically achieved by substituting some or all of the aggregate with electrically conductive fillers. By adding these fillers, the resistivity of the concrete can be controlled. There are three main types of electrically conductive fillers used in conductive concrete: polymer, carbon, and metal. Among these, carbon and metal fillers are the most commonly utilized [1]. Carbon-based fillers include materials such as graphite, carbon powder, and carbon fiber (CF). Metal fillers can include steel fiber and steel scraps. When carbon fiber (CF) is used as a conductive filler in concrete, it offers several advantages over conventional concrete. CF provides greater electrical conductivity, meaning it is more effective at conducting electricity [1]. Additionally, it enhances the mechanical properties of the concrete, making it stronger and more durable. By incorporating these conductive fillers into the concrete mixture, conductive concrete is able to exhibit improved electrical properties and conductivity compared to regular concrete. This makes it suitable for applications that require electrical conductivity, such as electromagnetic shielding, grounding systems, and specialized infrastructure where electrical continuity is essential.

Electrically conductive concrete is a remarkable material that offers not only the structural properties of conventional concrete but also exceptional mechanical and electrically conductive properties. It is relatively simple to prepare and can be sourced from a wide range of materials, making it

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convenient for construction projects. Furthermore, conductive concrete exhibits an extended service life and proves to be cost-effective. One notable advantage is its weight is lighter or similar to traditional concrete, which contributes to its versatility. Conductive concrete has found widespread applications in various fields, including deicing surfaces, providing electromagnetic shielding, establishing efficient grounding systems, creating anti-static flooring, and enabling cathodic protection for reinforced concrete structures. These applications capitalize on the excellent electrical conductivity and other favorable characteristics of conductive concrete, showcasing its immense potential and utility in diverse scenarios [2], [3], [4], [5], [6], [7], [8].

In today's world, the growing threat of electromagnetic pulse (EMP) events poses a significant risk to society, business operations, and critical infrastructure. The need to protect key facilities such as the electric grid, sensitive data centers, and vital communication lines has become a global concern. EMP incidents can be categorized into two types: intentional electromagnetic interference (IEMI) and high-altitude electromagnetic pulse (HEMP). It is alarming that even a nuclear weapon detonated in the high atmosphere can generate a HEMP, while terrorists and criminals can readily manufacture IEMI threats [9]. Consequently, the implementation of effective electromagnetic shielding measures has become imperative to safeguard against these threats. The importance of electromagnetic shielding in today's world cannot be overstated, as it plays a crucial role in mitigating the potential devastating impacts of EMP events.

EMI shielding is a crucial process aimed at protecting an area from radio wave or microwave radiation by creating a barrier that prevents the penetration of such radiation. In recent years, there has been significant research focused on the development of effective EMI shielding techniques [10]. Traditionally, metals have been widely used for EMI shielding, both in bulk form and as coatings. Sheet aluminum, for example, is commonly employed to create electrical enclosures. Another approach is the use of Faraday cages, shields, or Hoffman Boxes, which are constructed using conducting materials or conducting material mesh enclosures to shield against low-frequency electric fields.

However, most shields are not completely solid. They often feature access covers, doors, cable holes, ventilation holes, switches, displays, and joints/seams, which can significantly compromise their effectiveness by creating openings for radiation leakage. To address this challenge, EMI gaskets are used to seal the joints, ensuring both resilience and effective shielding [10]. In practical terms, the shielding effectiveness of the material itself is less problematic at higher frequencies compared to the leakage through apertures [11]. To conduct precise EMI and electromagnetic compatibility (EMC) measurements, anechoic chambers are utilized. These chambers provide complete isolation from external signal interference, resulting in unparalleled technical precision. Anechoic chambers are fully sealed rooms constructed with materials that absorb electromagnetic waves, and the outer framework is typically a "Faraday cage." The interior setup of the anechoic chamber provides an environment that minimizes external electromagnetic influences during EMI and EMC testing and analysis. The walls are covered with pyramidal absorbers to reduce the effect of electromagnetic field reflections and to keep the EM field distribution uniform. Polyurethane is a commonly used material in anechoic chambers for electromagnetic shielding [12]. However, the authors in [13] have used pyramidal-shaped conductive concrete as a viable substitute for commercially available absorbers and found out that the shielding effectiveness of the pyramidal conductive concrete samples was approximately 65 dB which is better than the commercial performance of 50dB using polyurethane. Because of its great performance, the obvious cost savings of employing conductive concrete as an anechoic absorber, and the ease with which it can be created and adjusted to meet the needs of the user, it has been concluded in [13] that conductive concrete is the best material suitable to be used in anechoic chambers.

The main focus of the current research is to develop a dielectric mixing model for estimating the complex permittivity of any conductive concrete mixture. This estimation is crucial for determining the required thickness of conductive concrete needed to achieve a desired level of protection. To achieve this objective, the relative complex permittivity of the concrete mixture is estimated by measuring the scattering parameters of the concrete samples using a rectangular waveguide in the c-band frequency range. The scattering parameters, namely S11 and S21, provide information about the levels of reflection and attenuation caused by the concrete samples, enabling the determination of their dielectric properties. A dielectric mixing model is then developed based on the volume percentage and dielectric properties of individual constituents in the concrete mixture. With the complex permittivity of the mix obtained, the necessary thickness of conductive concrete mix required for a specific level of attenuation can be determined.

II. EXPERIMENTAL SETUP USING A RECTANGULAR WAVEGUIDE

The effective complex dielectric permittivity of the conductive concrete is obtained by using a rectangular waveguide in a middle frequency range such as the c- band (3.95GHz – 5.85GHz) frequency range. The conventional and conductive concrete mixes were cast in the form of small blocks with thicknesses of 1cm, 2cm and 5cm and were tested in the rectangular waveguide to obtain the scattering parameters S_{11} and S_{21}. The scattering parameters are used to measure the levels of reflection and attenuation due to the presence of the concrete samples. This can be used to estimate the dielectric properties of the concrete as explained in the next section. Two different concrete mixes such as the conducive concrete with carbon and 1.5% steel fiber and the conventional concrete without any carbon or steel fiber cast in the form of small cubes were used for measurement. These cubes were cut into small blocks of varying thicknesses

FIGURE 1. Conductive concrete with thicknesses of 5cm, 2cm and 1cm respectively.

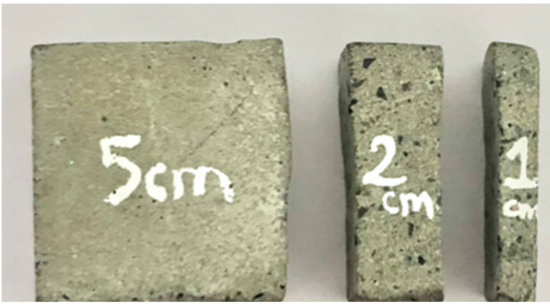

FIGURE 2. Conventional concrete with thicknesses of 5cm, 2cm and 1cm respectively.

(1cm, 2cm and 5cm) in order to obtain a reliable relative complex permittivity. Figure 1 and Figure 2 shows the images of conductive and conventional concrete with varying thicknesses, respectively.

In order to accurately measure the scattering parameters of the concrete blocks, a rectangular waveguide with a cutoff frequency of 3.152 GHz was utilized as a sample holder. The concrete blocks were precisely cut to fit into the waveguide, ensuring that there was no unwanted signal leakage inside the waveguide. This setup is depicted in Figure 3. To calibrate the waveguide, a vector network analyzer (VNA) was set to waveguide mode, and a calibration technique known as transmission-through-line (TRL) calibration was performed. TRL calibration helps in accurately characterizing the scattering parameters of the waveguide system by accounting for the effects of the waveguide and connectors used in the setup. By performing this calibration, accurate measurements of the scattering parameters of the concrete blocks can be obtained.

III. DIELECTRIC PERMITTIVITY CALCULATION

To calculate the complex dielectric permittivity of the two concrete mixes based on the obtained scattering parameters, a modified version of the Nicholson Ross Weir (NRW) method called the new non-iterative method was employed [14]. The new non-iterative technique is a variation of the NRW technique but with a different formulation. It is specifically designed to calculate the dielectric permittivity of materials with a permeability of 1. This technique offers several advantages. It is stable over a wide frequency range and is applicable to samples of any length. Unlike the NRW

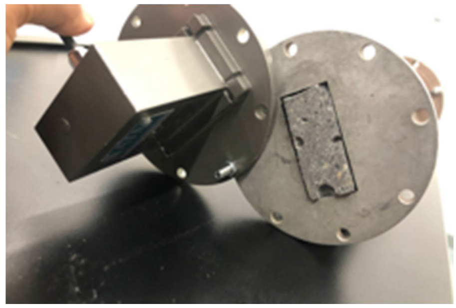

FIGURE 3. Representation of the concrete block placed inside the waveguide.

method, there is no divergence at frequencies within the sample that are multiples of one-half wavelength. Additionally, the new non-iterative method does not require an initial estimation of the permittivity and can perform the computations quickly [14]. This method enables the estimation of the complex dielectric permittivity of the concrete mixes based on the measured scattering parameters, providing valuable insights into the electromagnetic properties of the materials.

The new non- iterative method is performed through the following steps.

The reflection coefficient Γ is deduced as,

$$\Gamma = X \pm \sqrt{X^2 - 1} \tag{1}$$

where $|\Gamma| < 1$ is required for finding the correct root and,

$$\mathrm{X} = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}} \tag{2}$$

The transmission coefficient is given by the following formula,

$$\mathrm{T} = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \tag{3}$$

And the wavelength λ is given as follows,

$$\frac{1}{\lambda^2} = -\left(\frac{1}{2\pi L}\ln\left(\frac{1}{T}\right)\right)^2 \tag{4}$$

where L is the thickness of the sample in the waveguide.

Using λ_0 which is the free space wavelength and λ_c which is the cutoff wavelength

$$\lambda_{\mathrm{og}} = \frac{1}{\sqrt{\frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}}} \tag{5}$$

with the results from the reflection coefficient Γ, the effective permittivity $\in_{eff}$ is determined using the following equation,

$$\in_{eff} = \frac{\lambda_{og}}{\lambda}\left(\frac{1-\Gamma}{1+\Gamma}\right) \tag{6}$$

Hence the relative dielectric permittivity can be represented by,

$$\in_{\mathrm{r}} = \left(1 - \frac{\lambda_0^2}{\lambda_c^2}\right)\in_{\mathrm{eff}} + \frac{\lambda_0^2}{\lambda_c^2}\frac{1}{\mu_{\mathrm{eff}}} \tag{7}$$

Since the permeability of the concrete mixture is 1, the relative dielectric permittivity is given by,

$$\epsilon_r = \left(1 - \frac{\lambda_0^2}{\lambda_c^2}\right)\epsilon_{eff} + \frac{\lambda_0^2}{\lambda_c^2} \tag{8}$$

IV. DIELECTRIC MIXING MODEL DEVELOPMENT

Dielectric mixing models are valuable tools in understanding the macroscopic dielectric behavior of mixtures based on the properties of their individual constituents. These models establish a relationship between the overall dielectric constant of a mixture and the dielectric constants, volumetric content, and geometry of its constituents [15]. In the case of conductive concrete, the mixture comprises several components, including cement, silica fume (SF), ground granulated blast furnace slag (GGBS), water, sand, steel fiber, and carbon. On the other hand, conventional concrete contains all these constituents except steel fiber and carbon. To formulate an accurate mixing model, extensive research was conducted to verify the relative complex permittivity of each individual constituent in the chosen concrete mix. These permittivity values serve as crucial inputs for the mixing model. Table 1 provides a summary of the relative complex permittivity of each constituent. It is important to note that the dielectric constant of steel fiber is exceptionally large, nearly infinite, as it is a conductor. For calculation purposes, a value of approximately 1-j10000 was chosen to represent the dielectric constant of steel fiber in the mixing model. This enables the inclusion of the steel fiber's conductive properties within the formulation of the model.

Various models have been developed to estimate the bulk permittivity of heterogeneous materials, including the complex refractive index model (CRIM), Rayleigh model, Maxwell Garnett model, Brown model, and Wagner model [21]. For the specific conductive concrete mixture being studied, models such as the Maxwell Garnett model, Sihvola and Kong (SK) model, and Chang's models are suitable for estimating its dielectric constant based on the properties and proportions of its constituents. These models provide valuable insights into the electromagnetic properties and performance of the conductive concrete mixture.

A. MAXWELL GARNETT MODEL

The Maxwell Garnett model is given by [22],

$$\epsilon_{eff} = \epsilon_h + 3\,\epsilon_h \frac{\sum_{i=1}^{l} v_i \frac{\epsilon_i - \epsilon_h}{\epsilon_i + 2\epsilon_h}}{1 - \sum_{i=1}^{l} v_i \frac{\epsilon_i - \epsilon_h}{\epsilon_i + 2\epsilon_h}} \tag{9}$$

where the effective dielectric constant (ϵ_{eff}) is a function of ϵ_h (dielectric constant of the host) which is cement in the case of concrete mixture, ϵ_i (dielectric constants of inclusions), and v_i volumetric content of the inclusions).

B. SIHVOLA AND KONG (SK) MODEL

The SK model includes fractional volume of the constituents and the interaction part between each component. It is assumed that the inclusion particles are randomly distributed in a homogeneous background material which in the case of conductive concrete is cement, so that the dielectric properties are isotropic. SK model is given by [23],

$$\epsilon_{eff} = \epsilon_m + \frac{\sum_{i=1}^{n} v_i(\epsilon_i - \epsilon_m)\frac{3\epsilon_m}{\epsilon_i + 3\epsilon_m}}{1 - \sum_{i=1}^{n} v_i \frac{\epsilon_i - \epsilon_m}{\epsilon_i + 2\epsilon_m}} \tag{10}$$

where ϵ_i is the dielectric constant of each embedded material, v_i is the volume fraction occupied by the i^{th} embedded material and ϵ_m is the dielectric constant of the host which is cement in the case of concrete mixture.

TABLE 1. Relative complex permittivity of individual constituents [16], [17], [18], [19], [20].

Constituent	Relative Complex Permittivity (F/m)
Cement	3.7031- j0.0224
SF	2.785 - j0.2243
GGBS	6.59 - j0.24
Water	78.073 - j13.086
Sand	2.6 - j0.03
Steel Fiber	1 - j10000
Carbon	12 – j5

C. CHANG'S MODEL

Chang's model for n-phase materials is equal to the sum of each constituent's volume fraction and dielectric constant. The Chang's model is given as follows [23],

$$\epsilon_{eff} = c\left\lfloor \sum_{i=1}^{n} v_i\,\epsilon_i^{\alpha} \right\rfloor^{\beta} + k \tag{11}$$

where α and β are known constants and c and k are statistical parameters.

V. RESULTS AND DISCUSSION

This section presents the results of the waveguide measurement and the formulation of the dielectric mixing model. Comparisons between attenuation and thickness of the conductive mixtures are also presented in this section.

Figure 4 shows the comparison made between the scattering parameters S_{11} and S_{21} for the conductive block at 1cm, 2cm and 5cm. When the samples were placed in the waveguide, a small gap at the edge of the filled waveguide was observed. The measurements were conducted twice, once with air gap and another time with a small piece of Aluminum foil filling the air gap. It can be inferred from the plots that although there is no much change in the S_{11} values, the attenuation has increased vastly after minimizing the air gaps using an aluminum foil in the case of S_{21}. For instance, the attenuation was around-35dB for conductive concrete with

5cm thickness whereas the attenuation increased to −45db when the air gap was minimized, hence leading to a 10dB difference in the attenuation value. However, there was no noticeable change in the case of the conventional concrete. The magnitude and angle of S_{11} and S_{21} were measured using the VNA for the sample inside the waveguide and were plotted against frequency for the conductive and conventional concrete as shown in Figures 5-8.

A. DIELECTRIC PERMITTIVITY OF CONDUCTIVE AND CONVENTIONAL CONCRETE MIXTURES

The new non- iterative method discussed in Section IV was employed to calculate the complex dielectric permittivity of the two mixes from the obtained S parameter. The dielectric permittivity was estimated for conductive and conventional concrete blocks with 1cm and 5cm thickness respectively. A MATLAB code was developed for estimating the complex dielectric permittivity using the new non-iterative approach. The real and imaginary part of the relative permittivity for the conductive and conventional concrete were plotted against frequency and is shown in Figure 9 and Figure 10. The mean complex relative dielectric permittivity of conductive concrete and conventional concrete were found to be 22.57- j2.22 F/m and 5.45- j0.3091 F/m respectively from Figure 9 and Figure 10.

B. MIXING MODEL FORMULATION

Different mixing models were assessed by comparing their dielectric permittivity results with the measured permittivity in order to choose the best model for the developed concrete mixture.

1) MAXWELL GARNETT MODEL

Table 2 compares the value of the dielectric constant obtained by applying Maxwell Garnett model in Equation 9 and the measured dielectric constant values. It can be inferred from Table 2 that although the differences between the calculated $\in_r$ value and the measured value is quite small for conventional concrete but the differences were very large for conductive concrete which makes the model unsuitable for accurately representing the samples effective dielectric constants, resulting in a weak correlation between the calculated value and the measured value.

2) SIHVOLA AND KONG MODEL

The dielectric constant values obtained using the SK model in Equation 10 were compared with the measured dielectric constant values and were recorded in Table 3.

Similar to the Maxwell Garnett model, the SK model resulted in large differences in the $\in_\mathbf{r}$ value for conductive concrete although the differences were quite small in the case of conventional concrete as shown in Table 3.

3) CHANG'S MODEL

This was the model chosen for the developed concrete mix as the calculated results from the model closely resembled the

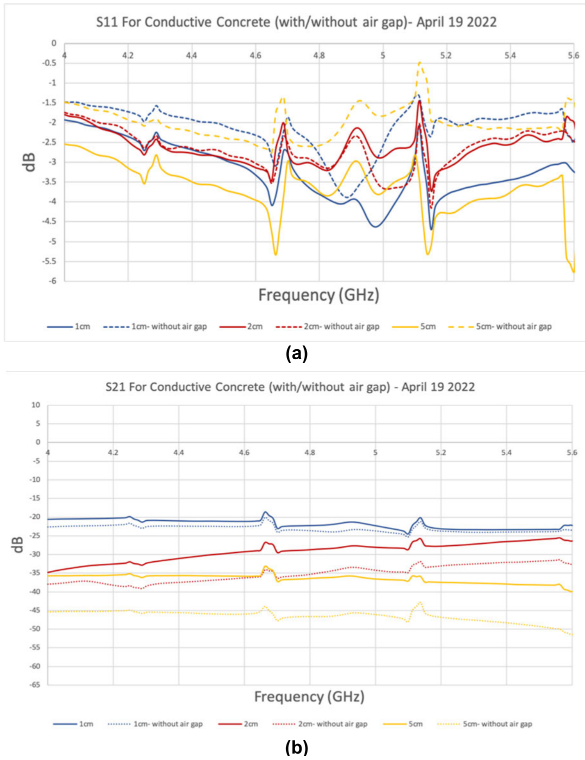

FIGURE 4. Comparison of scattering parameters S_{11} and S_{21} (a) with air gap; (b) without air gap.

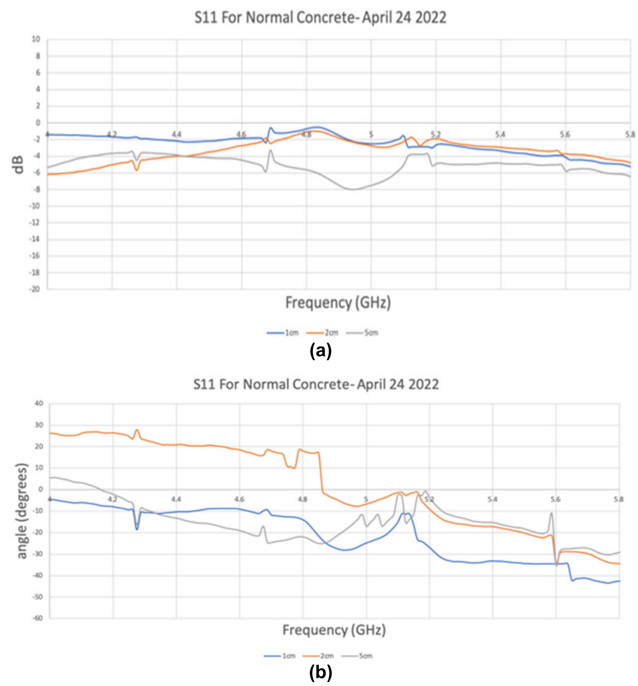

FIGURE 5. (a) magnitude (dB); (b) angle (degrees) measurement of the S_{11} parameter for normal concrete.

measured value. The general model is given in Equation 11. CRIM is one of the most used models for predicting the bulk permittivity of complex materials such as concrete.

In CRIM model, the most common shape factor

$$\alpha = 0.5 \tag{12}$$

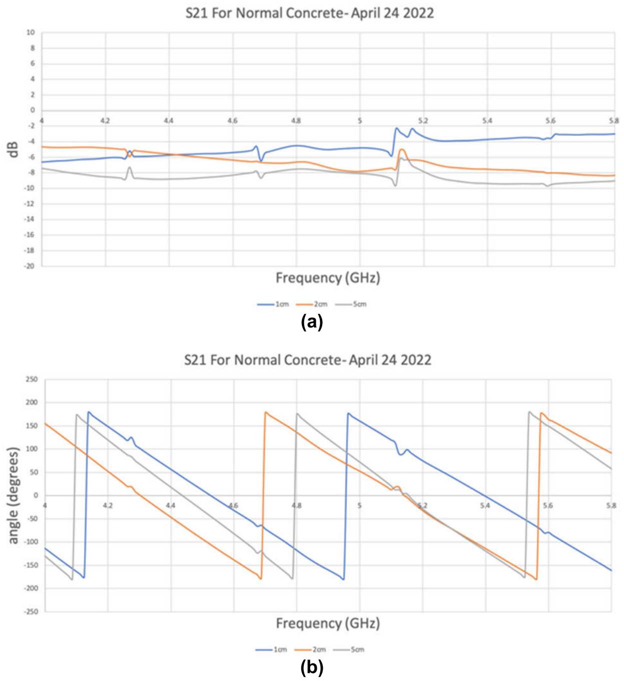

FIGURE 6. (a) magnitude (dB); (b) angle (degrees) measurement of the S_{21} parameter for normal concrete.

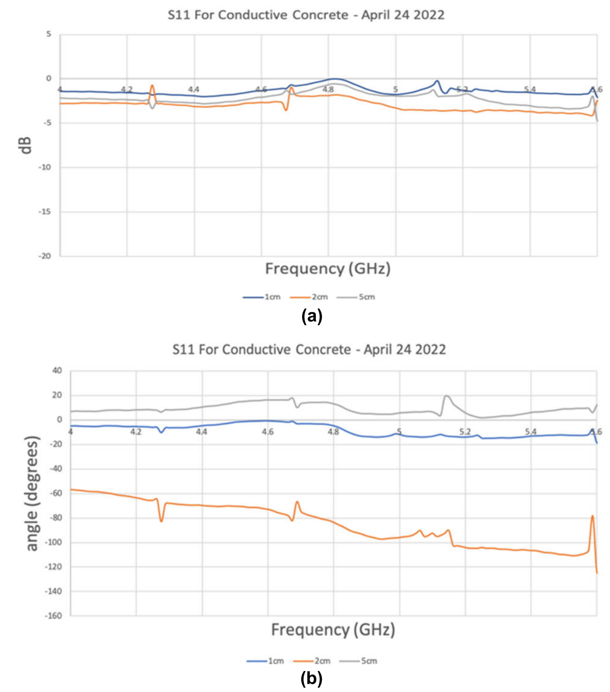

FIGURE 7. (a) magnitude (dB); (b) angle (degrees) measurement of the S_{11} parameter for conductive concrete.

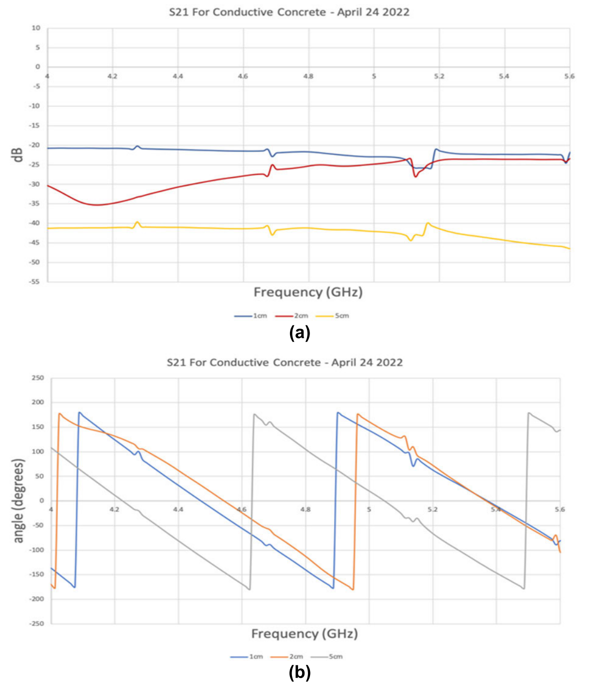

FIGURE 8. (a) magnitude (dB); (b) angle (degrees) measurement of the S_{21} parameter for conductive concrete.

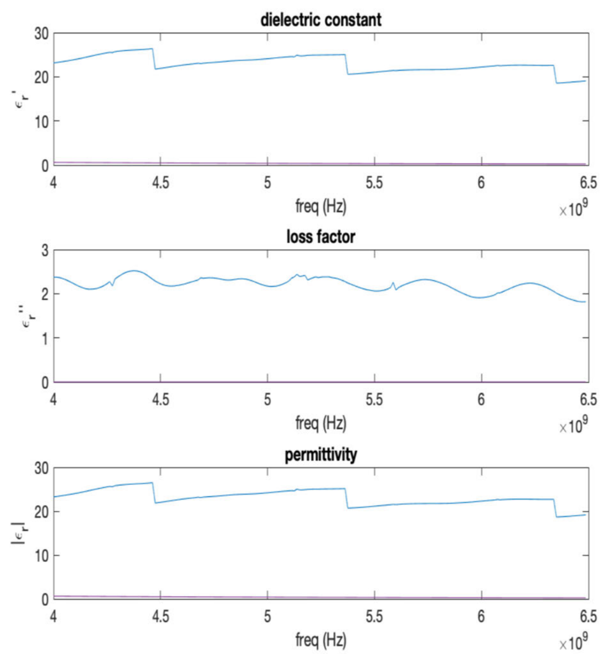

FIGURE 9. The relative complex permittivity vs frequency plots for conductive concrete.

and

$$\beta = \frac{1}{\alpha} = 2 \tag{13}$$

The statistical parameters c and k were set to 0.681 + j0.52 and −0.163 - j4.886 respectively. These values were obtained to give minimum differences between the calculated permittivity and the measured permittivity for both conductive and conventional concrete mixtures.

Hence, the final dielectric mixing model for the concrete mixes is given by,

$$\epsilon_{eff} = (0.681 + j0.52) \left\lfloor \sum_{i=1}^{n} v_i \epsilon_i^{0.5} \right\rfloor^2 + (-0.163 - j4.886) \tag{14}$$

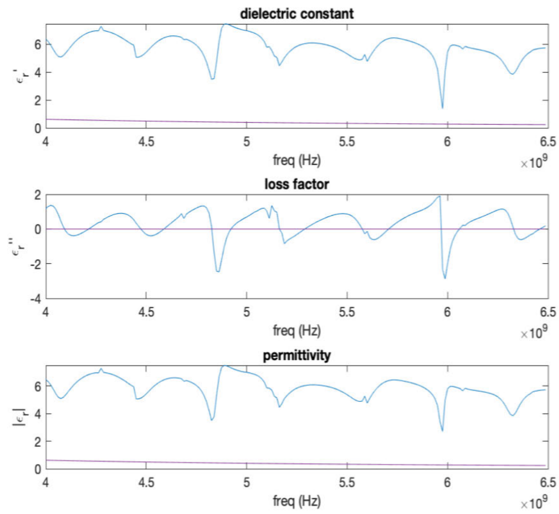

FIGURE 10. The relative complex permittivity vs frequency plots for conventional concrete.

From Table 4, it can be seen that the calculated $\in_r$ is almost equal to the measured $\in_r$ for both the concrete mixtures although there is a difference of about 2.339 + 1.0822i for conductive concrete and −2.2803 - 0.2i for conventional concrete. The individual dielectric permittivity of the constituents such as silica fume, GGBS, water, sand, steel fiber and carbon were obtained at different frequency ranges from literature which is not the same as the measurement frequency range, hence this might have added certain discrepancy in the final result of estimating the effective permittivity using the mixing model thus leading to the differences in the calculated and measured $\in_r$ values

C. RELATIONSHIP BETWEEN THICKNESS AND TOTAL LOSS

The thickness of the concrete sample required for any attenuation at frequencies of concern can be determined by knowing the relative complex permittivity of the concrete mixture using the developed dielectric mixing model.

When a signal is passed through a dielectric concrete sample in free space, reflections occur at the boundary of the air medium as well as inside the concrete sample and attenuation occurs within the sample. Hence, the total loss is given as follows.

$$\text{Total loss (dB)} = (2 \text{ x Reflection loss(dB)}) + \text{Attenuation loss (dB)} \quad (15)$$

The reflection loss is given in terms of the intrinsic impedance of the dielectric sample (η_2) and air (η_1).

$$\text{reflection loss}(\Gamma) = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \quad (16)$$

where the relative intrinsic impedance of air (η_1) is equal to 1 and the relative intrinsic impedance of the dielectric sample (η_2) is given by,

$$\eta_2 = \frac{1}{\sqrt{\in}} \quad (17)$$

TABLE 2. Comparison between calculated $\in_r$ and measured $\in_r$ using Maxwell Garnett method for conductive and conventional concrete.

Concrete Type	Calculated $\in_r$ (F/m)	Measured $\in_r$ (F/m)	Difference (F/m)
Conductive Concrete	7.2565 - j1.5839i	22.57 - j2.22	15.3135 - j0.6361
Conventional Concrete	5.1756 - j0.7595	5.45 - j0.3091	0.2744 + j0.4504

TABLE 3. Comparison between calculated $\in_r$ and measured $\in_r$ using Sihvola and Kong method for conductive and conventional concrete.

Concrete Type	Calculated $\in_r$ (F/m)	Measured $\in_r$ (F/m)	Difference (F/m)
Conductive Concrete	6.9918 - j1.6531	22.57 - j2.22	15.5782- j0.5669
Conventional Concrete	5.1587 - j0.9450	5.45 - j0.3091	0.2913+ j0.6359

TABLE 4. Comparison between calculate $\in_r$ and measured $\in_r$ using the formulated dielectric mixing model for conductive and conventional concrete.

Concrete Type	Calculated $\in_r$ (F/m)	Measured $\in_r$ (F/m)	Difference (F/m)
Conductive Concrete	20.2310 - j3.5122	22.57 - j2.22	2.339 + j1.2922
Conventional Concrete	7.7303 - j0.3191	5.45 - j0.3091	2.2803 + j0.01

The attenuation loss is given in terms of the thickness (L) and the attenuation coefficient (α).

$$\text{attenuation loss} = e^{-\alpha L} \quad (18)$$

where,

$$\alpha = \omega \left(\frac{\mu \in}{2} \sqrt{1 + \left(\frac{\in''}{\in'} \right)^2} - 1 \right)^{1/2} \text{ Np/m} \quad (19)$$

since μ =1 for the concrete mixture,

$$\alpha = \omega \left(\frac{\in}{2} \sqrt{1 + \left(\frac{\in''}{\in'} \right)^2} - 1 \right)^{1/2} \text{ x 8.686 dB/m} \quad (20)$$

Therefore, the total loss is given by,

$$\text{Total loss (dB)} = (2 \text{ x Reflection loss (dB)}) + \text{Attenuation loss (dB)} \quad (21)$$

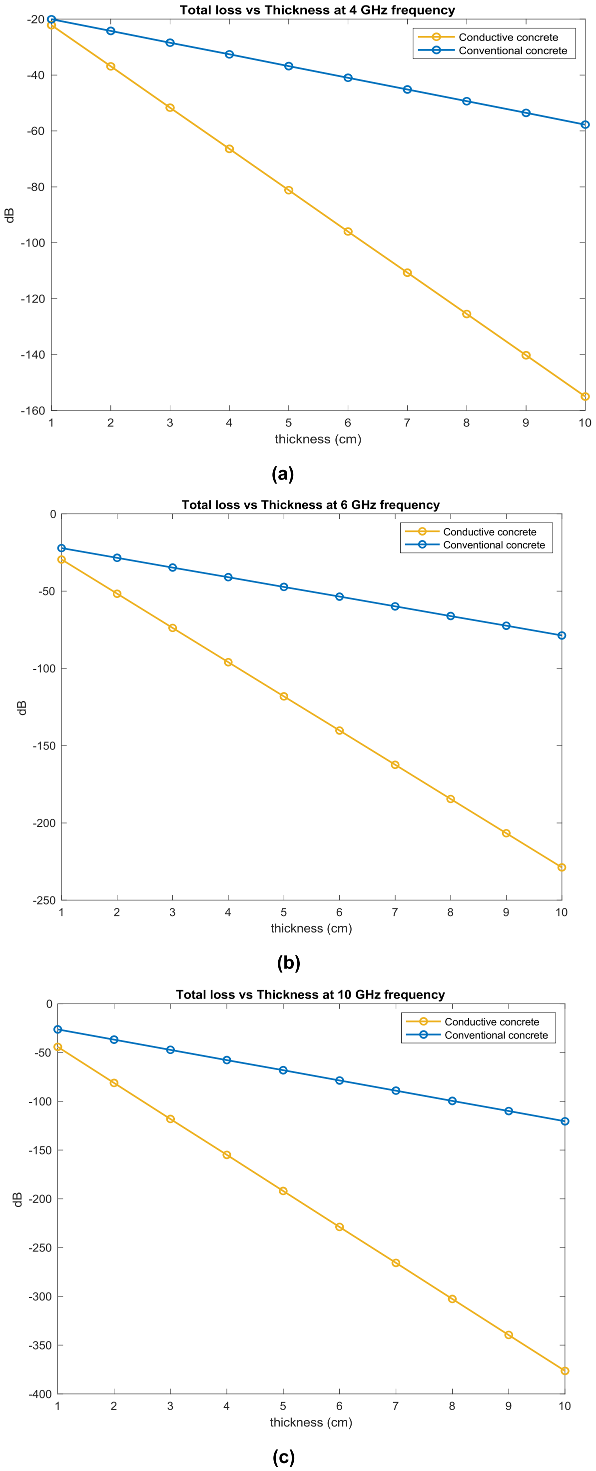

FIGURE 11. Total losses vs thickness for conductive and conventional concrete at a frequency of (a) 4GHz; (b) 6GHz; (c) 10GHz.

$$\text{Total loss (dB)} = 2 \text{ x } 20 \text{ x } \log_{10}(\Gamma) + 20 \log_{10}\left(e^{-\alpha L}\right) \tag{22}$$

From Equation 18, the attenuation constant α is a function of frequency. By rearranging Equation 22, thickness L of a concrete mixture for any desired frequency f is given by,

$$\text{Thickness (L (f))} = \times \frac{\ln\left(10^{\frac{(\text{Total loss(dB)} - 2\text{x}20 \text{ x}\log_{10}(\Gamma))}{20}}\right)}{-\alpha} \tag{23}$$

Attenuation vs thickness plots were generated theoretically for thicknesses varying from 1cm to 10cm at three different frequencies: 1GHz, 6GHz and 10GHz for both conductive and conventional concretes samples as shown in Figure 11. It can be inferred from the graphs that the attenuation increases with increase in the thickness of concrete sample for a given frequency in the case of both conductive and conventional concrete.

VI. CONCLUSION

A dielectric mixing model was formulated for the concrete mixture using the relative complex permittivity and volume percentages of its individual constituents such as silica fume, cement, GGBS, water, sand, carbon and steel fiber. In order to estimate the effective relative complex permittivity of the concrete mix, magnitude and angle of the scattering parameters S_{11} and S_{21} of the concrete samples were measured using a rectangular waveguide. The average relative complex permittivity of conductive concrete and conventional concrete were found to be 22.57- j2.22 F/m and 5.45-j0.3091 F/m respectively.

The results obtained from the formulated dielectric mixing model using the Chang's model were very close to the measured value with a very small difference between the calculated and measured value. This difference could be due to the different frequency ranges at which the dielectric permittivity of the individual constituents was obtained from literature. Moreover, the dielectric constant obtained from the developed dielectric mixing model was used to determine the thickness of the concrete samples required for any desired attenuation at frequencies of concern. Eventually, the developed dielectric mixing model along with the formula relating the required level of attenuation to the thickness of concrete sample could be used as an industrial standard model to make concrete mixtures for any application at any desired frequency.

As a future work, separate tests could have been performed with proper equipment in order to determine the accurate dielectric permittivity of individual constituent materials such as SF, cement, GGBS, water, sand, carbon and steel fiber at the measurement frequency.

REFERENCES

[1] B. Swaked, N. Qaddoumi, S. Yehia, S. Farhana, and L. Nguyen, "Conductive concrete for smart cities applications," in *Proc. AEIT Int. Annu. Conf. (AEIT)*, Sep. 2019, pp. 1–5, doi: 10.23919/AEIT.2019.8893415.

[2] A. Sassani, A. Arabzadeh, H. Ceylan, S. Kim, S. M. S. Sadati, K. Gopalakrishnan, P. C. Taylor, and H. Abdualla, "Carbon fiber-based electrically conductive concrete for salt-free deicing of pavements," *J. Cleaner Prod.*, vol. 203, pp. 799–809, Dec. 2018, doi: 10.1016/j.jclepro.2018.08.315.

[3] H. C. F. Cordon, F. B. Tadini, G. A. Akiyama, V. O. D. Andrade, and R. C. D. Silva, "Development of electrically conductive concrete," *Cerâmica*, vol. 66, no. 377, pp. 88–92, Mar. 2020, doi: 10.1590/0366-69132020663772775.

[4] S. Yehia and J. Host, "Conductive concrete for cathodic protection of bridge decks," *ACI Mater. J.*, vol. 107, no. 6, p. 577, 2010, doi: 10.14359/51664044.

[5] D. Zhang, H. Le, X. Yan, T. Yuan, and J. Li, "Preparation of steel fiber/graphite conductive concrete for grounding in substation," in *Proc. ICHVE Int. Conf. High Voltage Eng. Appl.*, Sep. 2014, pp. 1–4, doi: 10.1109/ICHVE.2014.7035490.

[6] A. Downey, A. D'Alessandro, F. Ubertini, and S. Laflamme, "Automated crack detection in conductive smart-concrete structures using a resistor mesh model," *Meas. Sci. Technol.*, vol. 29, no. 3, Mar. 2018, Art. no. 035107, doi: 10.1088/1361-6501/aa9fb8.

[7] B. Han, S. Ding, and X. Yu, "Intrinsic self-sensing concrete and structures: A review," *Measurement*, vol. 59, pp. 110–128, Jan. 2015.

[8] S. Yehia, N. Qaddoumi, M. Hassan, and B. Swaked, "Evaluation of conductive concrete for anti-static flooring applications," *Proc. SPIE*, vol. 9433, pp. 182–187, Apr. 2015, doi: 10.1117/12.2179190.

[9] L. Nguyen, "Conductive concrete structures for EMP protection of critical infrastructure facilities," *IEEE Lett. Electromagn. Compat. Pract. Appl.*, vol. 1, no. 1, pp. 26–33, Mar. 2019, doi: 10.1109/LEMCPA.2019.2922877.

[10] D. Chung, "Materials for electromagnetic interference shielding," *Mater. Chem. Phys.*, vol. 255, Apr. 2020, Art. no. 123587, doi: 10.1016/j.matchemphys.2020.123587.

[11] G. Sindura, K. R. Prakash, and P. Salil, "Control of electromagnetic waves through electromagnetic shielding," in *Proc. Int. Conf. Emerg. Trends Electr. Comput. Technol.*, Mar. 2011, pp. 448–452, doi: 10.1109/ICETECT.2011.5760158.

[12] A. S. Hoang, "Electrical conductivity and electromagnetic interference shielding characteristics of multiwalled carbon nanotube filled polyurethane composite films," *Adv. Natural Sci., Nanosci. Nanotechnol.*, vol. 2, no. 2, Jun. 2011, Art. no. 025007, doi: 10.1088/2043-6262/2/2/025007.

[13] T. Khalid, L. Albasha, N. Qaddoumi, and S. Yehia, "Feasibility study of using electrically conductive concrete for electromagnetic shielding applications as a substitute for carbon-laced polyurethane absorbers in anechoic chambers," *IEEE Trans. Antennas Propag.*, vol. 65, no. 5, pp. 2428–2435, May 2017, doi: 10.1109/TAP.2017.2670538.

[14] R. Kg. (2012). *Measurement of Dielectric Material Properties*. Rohde-schwarz.com. [Online]. Available: https://www.rohde-schwarz.com/hk/applications/measurement-of-dielectric-material-properties-application-note_56280-15697.html

[15] A. Sihvola, *Electromagnetic Mixing Formulas and Applications*. London, U.K.: IEE Publishing, 1999.

[16] Y. Makul, *Study of Interaction Between Reinforced Concrete and Microwave Energy Using a Single-Mode Square Waveguide: Theory and Experiment*. Bangkok, Thailand: Phranakhon Rajabhat Univ., 2014, pp. 62–63.

[17] C. A. Edwards, K. M. Donnell, and C. R. Shearer, "Microwave materials characterization of geopolymer precursor powders," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf. (I2MTC)*, May 2018, pp. 1–5, doi: 10.1109/I2MTC.2018.8409709.

[18] C. Mätzler and A. Murk, "Complex dielectric constant of dry sand in the 0.1 to 2 GHz range," Inst. Appl. Phys., Univ. Bern, Bern, Switzerland, Tech. Rep., 2010.

[19] M. Hotta, M. Hayashi, M. T. Lanagan, D. K. Agrawal, and K. Nagata, "Complex permittivity of graphite, carbon black and coal powders in the ranges of X-band frequencies (8.2 to 12.4 GHz) and between 1 and 10 GHz," *ISIJ Int.*, vol. 51, no. 11, pp. 1766–1772, 2011, doi: 10.2355/isijinternational.51.1766.

[20] T. Meissner and F. J. Wentz, "The complex dielectric constant of pure and sea water from microwave satellite observations," *IEEE Trans. Geosci. Remote Sens.*, vol. 42, no. 9, pp. 1836–1849, Sep. 2004, doi: 10.1109/TGRS.2004.831888.

[21] J. Qian, S. Yan, Z. Li, L. Yu, X. Wang, Z. Zhang, J. Sun, and X. Han, "Modification of the Maxwell–Wagner heterogeneous dielectric model for heterogeneous polymers and emulsions," *Polymers*, vol. 14, no. 13, p. 2743, Jul. 2022, doi: 10.3390/polym14132743.

[22] A. Hashemi, K. E. Kurtis, K. M. Donnell, and R. Zoughi, "Empirical multiphase dielectric mixing model for cement-based materials containing alkali-silica reaction gel," *IEEE Trans. Instrum. Meas.*, vol. 66, no. 9, pp. 2428–2436, Sep. 2017, doi: 10.1109/TIM.2017.2707927.

[23] C. Chang, J. Chen, and T. Wu, "Dielectric modeling of asphalt mixtures and relationship with density," *J. Transp. Eng.*, vol. 137, no. 2, pp. 104–111, 2011, doi: 10.1061/(asce)te.1943-5436.0000204.

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