Electromagnetic Characterizations of Cement Using Free Space Technique For The Application of Buried Object Detection

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Abstract

A free space technique is invoked to characterize the electromagnetic properties of different types of cement: Mortar only, mortar with welded wired meshes (BRC) for concrete reinforcement (Concrete), and cement immersed with PVC tubes at the Ku-band from 12 GHz to 18 GHz. The base mixture of the prepared samples is based on cement, sand, and water, as a binding agent, to be as mortar. The measurement setup consists of highly focused transmitting and receiving horn antennas that are connected, respectively, to port 1 and port 2 of the Professional Network Analyzer (Agilent PNA 8720). The samples are inserted between the two antennas to measure, S_{11} and S_{12}, the S-parameters. Using Agilent's open ended coaxial probe, the dielectric constant and loss factor are measured at different locations. A Finite Element Method (FEM) based on the formulations of High Frequency Structure Simulator (HFSS) is conducted to validate the measured results. The measured dielectric constant and loss factor are assigned in the HFSS simulations. Good agreements are obtained for the simulated and measured S-parameters within relative errors less than 1% and 2%, respectively.
Key words- mortar, concrete, FEM, horn antennas.

دراسة الخصائص الكهرومغناطيسية للسمنت باستخدم تقنية الفضاء الحر لتطبيقات دراسة الاجسام المدفونة

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الخلاصة

تم استدعاء تقنية الفضاء الحر لتوصيف الخصائص الكهرومغناطيسية من أنواع مختلفة من الأسمنت: هاون فقط، هاون مع شبكة سلكية ملحومة (BRC) لتسليح الخرسانة، والاسمنت مغمورة مع أنابيب PVC خلال الترددات من 12 GHz إلى 18 GHz. ويعتمد الخليط بشكل اساسي على الاسمنت والرمل والماء لتكون هاون. تمت القياسات باستخدام عدسات شديدة التركيز و هوائيات الإرسال والاستقبال التي ترتبط على التوالي إلى ماخذ 1 و 2 من محلل الاشارة (اجيلنت 8720). تم إدراج العينات بين الهوائيات اثنين لقياس، S_{11} S_{12}. باستخدام الطرف ذو النهاية المفتوحة لاجيلنت القياس ثابت العزل الكهربائي (السماحية) و عامل الخسارة في مواقع مختلفة. وأجريت تحليلات عددية (FEM) استنادا إلى تركيبات عالية التردد في محاكي الهياكل (HFSS) للتحقق من صحة النتائج المقاسة. يتم تعيين عازلة ثابت و عامل خسائر في عمليات المحاكاة HFSS. تم الحصول على اتفاق جيد بين نتائج المحاكاة وقياسات المختبرية بنسبة خطاء أقل من 1٪ و 2٪ على التوالي.
الكلمات المفتاحية – خليط اسمنتي , خرسانة , طريقة العناصر المحددة , هوائيات بوقية

Introduction

Cement based different mixtures such as cement paste, mortar, concrete are principally used in the erection and civil engineering industries [1]. Although, studying the physical properties of such mixtures is an essential characterization of the mechanical qualities [2], the knowledge of their electromagnetic properties became very important determination for building health monitoring systems and indoor wireless communication applications [3]-[5]. This is because the scattering parameters, reflection and transmission coefficients, are severally affected by the constitutive parameters of buildings and walls.

Literally, many non-destructive electromagnetic techniques have been attempted to obtain the constitutive parameters of different mixtures of cement [3] in the microwave range. For example, in [3], the combination of free-space reflection and transmission methods was invoked to characterize the complex refractive index of concrete at 57.5 GHz.

The microwave reflection coefficient measurements at 1.9 GHz and 4.0 GHz for smooth and rough exterior building surfaces based on different composites of limestone blocks, glass, and brick were characterized in [4] by resolving individual reflected signals temporally and spatially using a spread-spectrum sliding correlation system with directional antennas. The measurements of reflection and transmission spectra of cement, based blocks of mortar and concrete, were obtained from a microwave oscillator modulated by a 1-kHz signal at the X-band in [5] to specify the water-to-cement ratio and curing conditions.

Although, such material, cement, mortar and concrete, are nonmetallic materials, their unique electromagnetic properties can be presented in a dielectric constant and/ or conductivity [6] by elaborating nondestructive methods. In [7], a free space technique and contactless method, such examples of the non-destructive methods, were used for measuring the required curing time trough monitoring the moisture contents in cement-based composites.

In this paper, a simple and inexpensive microwave investigation, which is appropriate for industrial based applications to measure the complex permittivity of cement based material at Ku-bands (12-18) GHz, is applied. In section II, the methodology of measurements is discussed. The electromagnetic characterizations are discussed in section III. The paper is concluded in section IV.

Methodology and Measurement Techniques

In this section, the samples preparation, measurement setups, and numerical simulations are discussed as follows:

A. Samples preparation

Three samples are performed based on different compositions of cement. The first sample, to be called as mortar, is made of cement, sand, and water as a binding agent. Another sample, which is called concrete, based on immersing BRC inside a mortar composite, is considered.

The distance from the BRC layer to another one is fixed at 7cm. The last sample of mortar composite is prepared to be filled with PVC tubes. The separation distance between tubes, center to center, inside the sample is considered as 6cm. The cross sectional area of all samples is considered as 28×28 cm^2 with a thickness of 4.4 cm. The same quantities of sand, cement, and water are used for the all prepared samples as listed in Table 1.

Table 1: Sand, cement, and water quantities of the prepared samples.

Material	Quantity
Sand (gm)	4000
Cement (gm)	2000
Water (ml)	1400

It is important to mention that the used type of cement in this paper is an industrial material of Ordinary Portland Cement (OPC) which is manufactured by Lafarge Malayan Cement Berhad which exceeds the quality requirements that is specified according to the Malaysian Standard MS 522: Part 1: 1989 Specifications for OPC.

B. Measurement techniques

The measurement setup, a free space technique, consists of transmitting and receiving horn antennas with focusing lenses that connected, respectively, to port 1 and port 2 of the Professional Network Analyzer (Agilent PNA 8720). The horn antennas are instrumented for transmitting and receiving the electromagnetic waves. The lenses are applied on the apertures of the antennas for focusing the emerged electromagnetic radiations. The antennas are separated, from the first aperture to another aperture, with 20 cm. This setup is used to perform S-parameter measurements, recorded by PNA, after introducing the sample under test between the horn antennas. In Fig. 1, the measurement setup for S-parameters of mortar, mortar filled with PVC tubes, than, welded wired mesh inside mortar composite, is presented. In general, the relative permittivity consists of real and imaginary parts depending on the frequency to be given as $\varepsilon_r(f)=\varepsilon_r'(f)-j\varepsilon_r''(f)$. The real part, $\varepsilon_r(f)$, is dielectric constant and the imaginary part, $\varepsilon_r(f)$, is the dielectric loss factor.

A typical measurement system using a coaxial probe method consists of a network or impedance analyzer, coaxial probe and software. Both the software and the probe are included in the 85070E dielectric probe kit. An external computer is needed in many cases to control the network analyzer through GPIB. The 82357A USB to GPIB interface provides a convenient and flexible way to realize this connection. For the PNA family of network analyzers the software can be installed directly in the analyzer and there is no need for an external computer. We have measured $\varepsilon_r'(f)$ and $\varepsilon_r''(f)$ using an Agilent 85070B dielectric probe kit and dielectric probe software 85070 E2.00 in the Ku band. The dielectric probe is calibrated using open circuit and short circuit with distilled water at a temperature of 25 ◦C.

Fig 1: The measurement setup of the free space technique

C. Numerical simulations

The numerical simulations for extracting the S-parameters are developed in this section. The Finite Element Method (FEM) simulations are carried out by Ansoft's HFSS full-wave simulator [10] to evaluate the S-parameters to validate the measured S-parameters. The S-parameters spectra, in terms of S_{11} and S_{21}, of the sample under test are evaluated by surrounding a small portion of the sample inside an air box as shown in Fig 2. To mimic a transverse electromagnetic mode, the top and bottom sides of the air box are assigned as perfect electric walls (PECs) and the other two sides as perfect magnetic walls (PMCs).

The front and the back sides are considered as port 1 and port 2, respectively, to face the normal incident of the wave propagation. The required values of permittivity by HFSS simulations are assigned parametrically with an initial guess from Agilent open ended coaxial probe measurements to match the simulated S-parameters to their identical based on measurements.

As can be seen in the flow chart, displayed in Fig. 3, the followed retrieving procedure to validate the measured relative permittivity is described. The effective complex permittivity for the sample under test is retrieved back from simulated results using Nicolson Rouse Wild (NRW) method for validation.

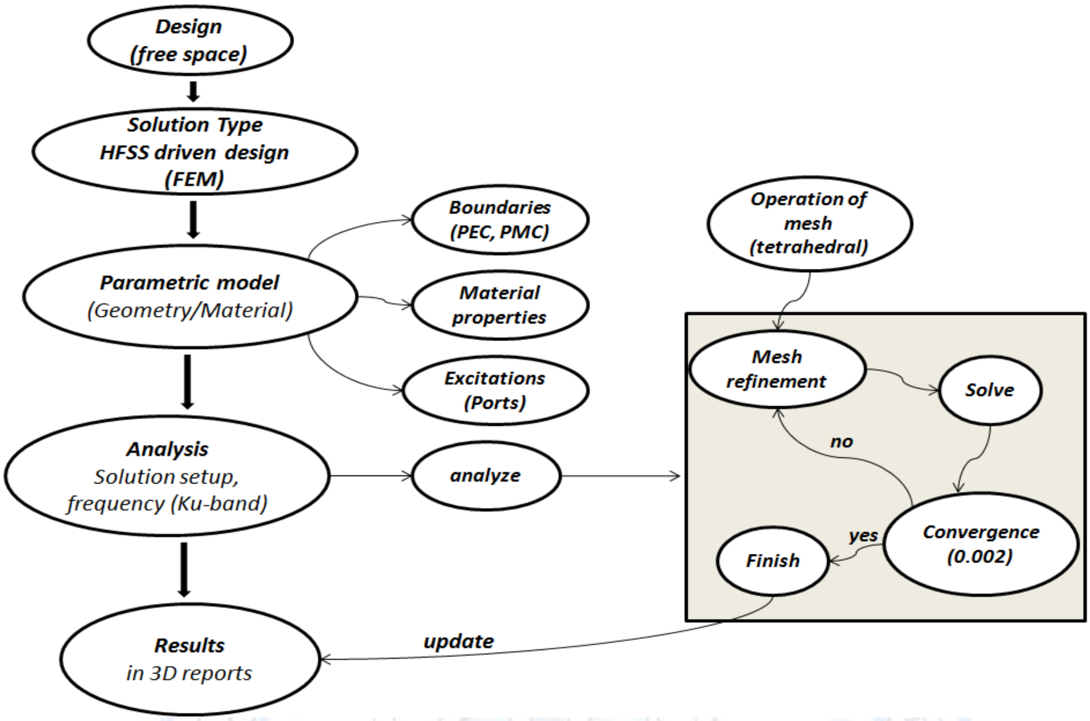

Fig 2: Finite Element Method (HFSS) simulation flowchart.

Results and Discussion

The regarded results from simulations and measurements are compared and discussed in this section. The obtained measurements from the open end waveguide are discussed too.

A. Open ended coaxial probe measurements

The permittivity of the material is measured by immersing the probe to the flat surface of the sample. The fringed fields at the end of the probe change according to the material properties of the sample surface. The reflection coefficient, presented by S_{11}, can be affected severely with the value of the complex permittivity.

The complex permittivity is a crucial parameter to describe the relationship between the material and the electromagnetic field. The real part of the complex permittivity measures the ability of the material to store the electric field while the imaginary part represents the dissipated energy. Fig. 3 shows the complex permittivity for three different samples (mortar, concrete, and mortar filed with tubes). The effects of adding the BRC and tubes are observed on both dielectric constant and the loss factor. It is found that, the pure cement shows the highest value of the complex permittivity in both real and imaginary parts which indicates that decreasing in the complex permittivity is due to the concrete and tubes compositions. Nevertheless, small variations of ripples are due to surface roughness which can be minimized by providing a good contact between the sample surface and the sensing area of the probe. The mean real permittivity is calculated to be 2.23, 1.57 and 1.74 for the mortar, cement filled with tubes and concrete, respectively. In the same manner, the imaginary part is 0.29, 0.14 and 0.13.

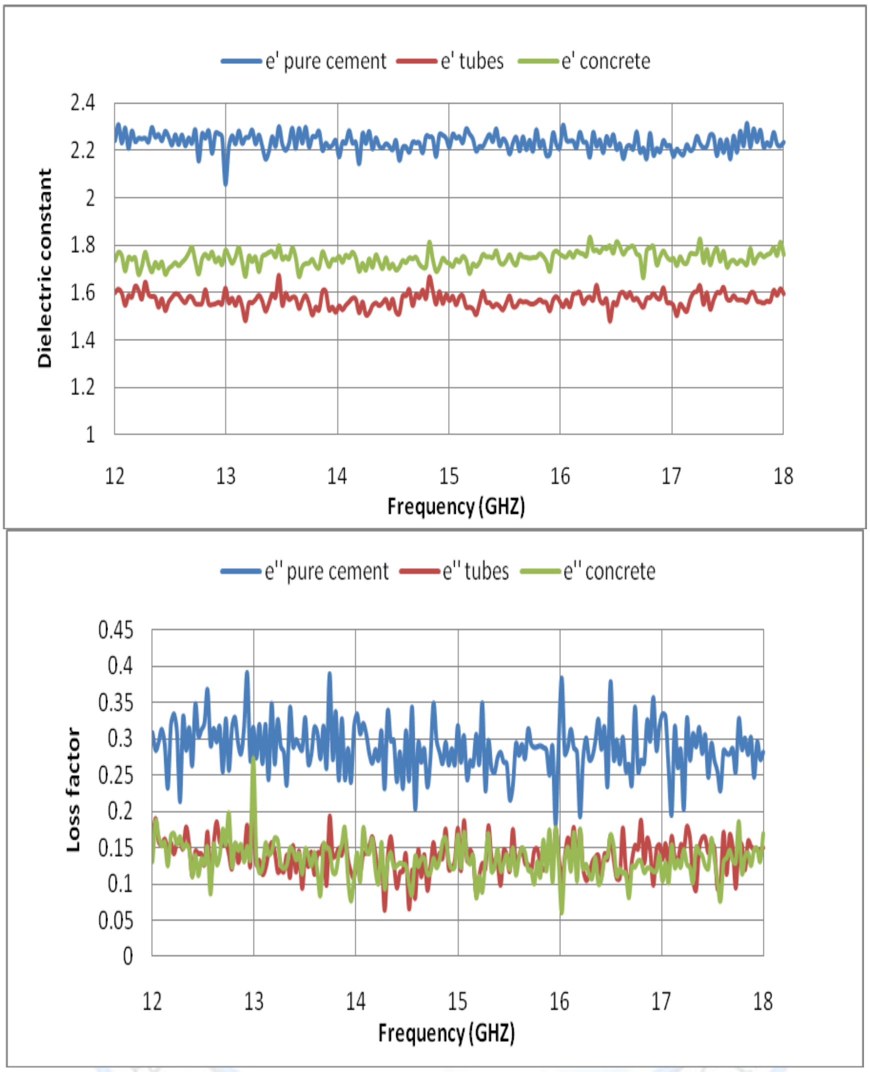

Fig. 3: The complex permittivity of mortar, concrete and mortar filed with PVC tubes;
(a) dielectric constant and (b) loss factor.

B. Free space technique measurements

Free-space technique is investigated for material characterizations of bulky size [2]. Applying such technique offers more flexibility and large coverage area by assuming far-field measurements. The measured complex permittivity is used as initial guess to determine the S-parameters in the FEM simulations at the Ku-band. The measured S-parameters based on free space technique are compared to those obtained from simulations. Fig. 4 shows an excellent matching between the measured and simulated S_{21}, while, S_{11} shows insignificant error due to the limitations in the free space measurements such as having launched plan wave in limited zone creates undesirable diffractions/reflections from the edges of the sample [8]. The mean errors corresponding to the measured data are listed in table 2.

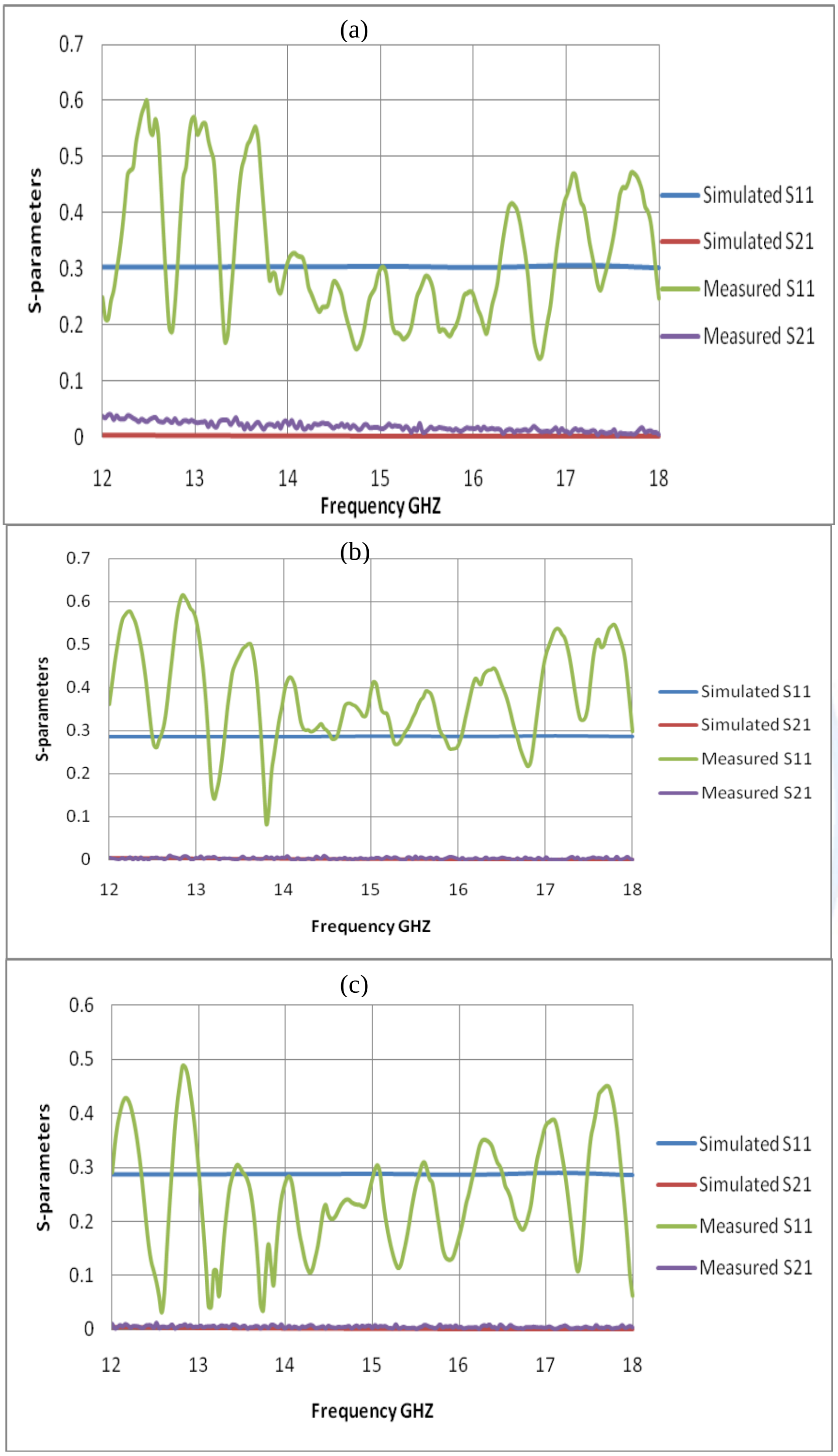

Fig 4: represents the measured and simulated results

Table 2: The mean relative errors of the simulated/ measured S-parameters

Sample	S_{11}	S_{21}
Mortar	0.022	0.016
Concrete	0.096	0.003
Tubes	0.040	0.003

From the general inspection, the three different samples show the same profile with different magnitudes of S_{11} and S_{21}. The value of the S_{21} magnitude is found to be very low, due to the material losses of sample under test as can be seen from the electric field distributions in Fig. 5.

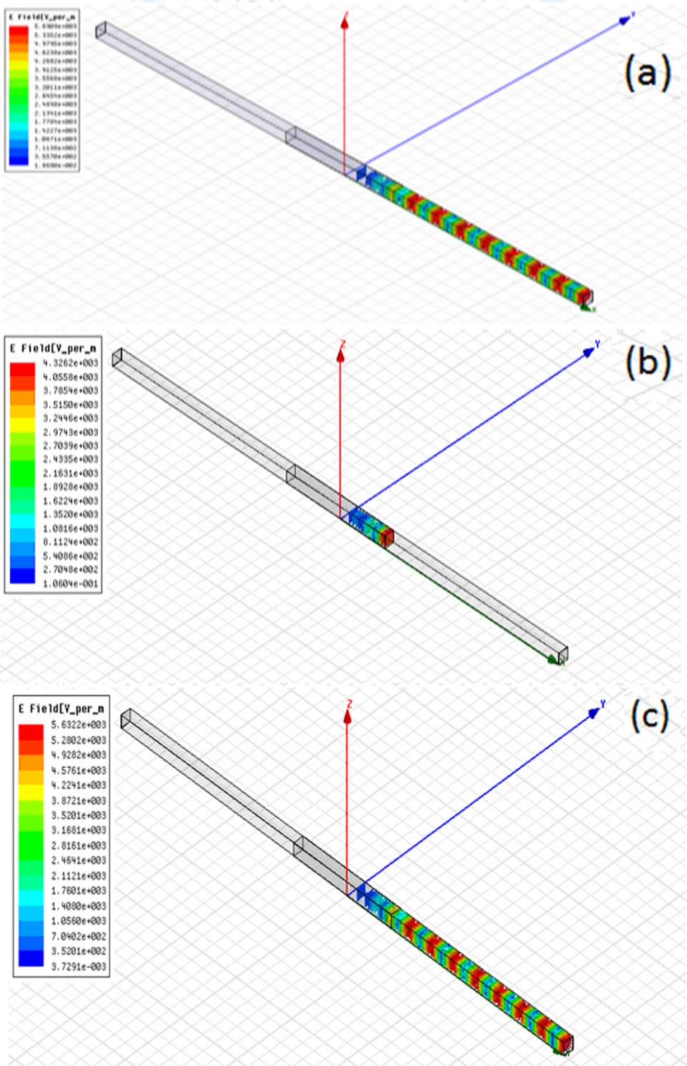

Fig 5: 3-D distributions of the impinging electric fields that evaluated from HFSS simulations (a) mortar, (b) concrete, and (c) mortar filled with PVC tubes.

	Measured (Average)	Simulated (HFSS)	Retrieved (Average)
Mortar	2.30-j0.30	2.50-j1.63	2.35-j1.60
Concrete	1.80-j0.15	2.20-j1.54	2.05-j1.34
Mortar Filled with PVC	1.60-j0.20	2.20-j1.54	2.12-j1.39

Conclusion

A free space microwave technique has been successfully applied for determination of the electrical properties of Mortar, concrete and cement filled with tubes at Ku-band from 12 GHz to 18 GHz. The transmission and reflection measurements have been done by placing the samples in between two propagating antennas. The measured results were compared to the simulated ones by using software simulation program which is defined as Finite Element Method (FEM). The numerical calculation was done by using HFSS. The input values required by HFSS for the dielectric constant and loss factor of all samples were gained from the measured results by using Agilent's open ended coaxial probe. Good agreement was suitably obtained for both the S_{11} and S_{21} results within 1% and 2% respectively for the sample placed in direct contact between two antennas.

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