Progress In Electromagnetics Research Letters, Vol. 89, 91–97, 2020

Monitoring the Dielectric Properties and Propagation Conditions of Mortar for Modern Wireless Mobile Networks

Mohammed A. Jawad[1], Mohammed A. Elwi[2], Ethar Y. Salih[3], Taha A. Elwi[4, *], and Zulkifly Abbas[1]

Abstract—Recently, modern wireless communication applications are extended to call high frequency bands including millimeter waves for 5G systems. Therefore, the propagation properties of such waves in different media have attracted many researchers. In this work, the results of the S-parameters measurements of mortar with four thicknesses are obtained using a nondestructive free space measurement technique for the frequency bands from 8 GHz up to 32 GHz. The obtained results of the dielectric properties and loss factors for the prepared mortar samples are realized. The variation in both the reflection and transmission coefficients and the dielectric properties with curing time conditions of mortar structure is examined. The dielectric properties of water are realized using the proposed method to subtract the effects of water contents from the prepared mortar samples. The effects of the sample thickness and relaxation frequency are considered. The obtained measurements are compared to the simulated results based on a full wave simulation software package of CSTMWS algorithms. Finally, excellent agreements are achieved between the simulated and measured results.

1. INTRODUCTION

Cement based materials, such as cement paste, mortar, and concrete, are extensively used in many structures in the construction filed [1]. The understanding of knowing the physical properties of such materials is important for evaluating the quality of signal propagation in many mobile communication systems including 5G networks [2]. For illustration, one of the most important parameters linked with mortar is curing time conditions, which relies on the water to cement ratio factor [3]. Microwave nondestructive technique has revealed immense interest for determining the properties and water contents in many materials [4]. In contrast, the electromagnetic characterization is needed in propagation related area, for instance, microwave propagation modeling to develop indoor wireless communication systems [2]. This is because the reflection and transmission characteristics of buildings and walls are relatively affected by materials dielectric properties [5]. It is obviously recognized that the dielectric properties of cement-based materials change during the curing time [4]. During the hydration process, water and cement molecules are joined chemically into a binder, transforming the initial free water into bound water; therefore, the dielectric properties of such composition are significantly affected [6].

Recently, several investigations have been established the capability of microwaves to identify the state and degree of hydration in cement-based materials [4]. By using a near-field microwave inspection technique, a strong correlation was shown between the magnitude of the reflection coefficients and the water-cement ratio [7]. Although the results are promising, only reflection properties of smooth

Received 9 September 2019, Accepted 15 December 2019, Scheduled 22 January 2020

* Corresponding author: Taha Ahmed Elwi (taelwi82@gmail.com).
[1] Department of Physics, University Putra Malaysia, Serdang, Selangor 43400, Malaysia. [2] Department of Building and Construction, University of Technology, Baghdad, Iraq. [3] Al-Nisour University College, Baghdad, Iraq. [4] Department of Communication Engineering, Al-Ma'moon University College, Baghdad, Iraq.

plane surfaces of the specimen can be investigated by this contacting method. Besides, reflection and transmission properties of such materials are not obtained. Based on the free space method given in [6], penetration of microwaves in lossy specimens with smooth, rough, and non-plane surfaces and their reflection and transmission properties can be investigated. Nevertheless, at high frequencies, millimeter wave ranges above 20 GHz, and the penetration through cement specimens is very difficult [7]. In practical applications, it is very striking to determine the dielectric properties of materials by using only amplitudes of the reflection and transmission coefficients [8].

In this paper, a simple and inexpensive measurement technique is invoked for the reflection and transmission spectra measurements of mortar. The effects of changing the mortar thicknesses on the relative retrieved dielectric properties with the proposed measurement technique are illustrated briefly. The main findings of this research have also been discussed. Finally, the concluding remarks of this work are highlighted.

2. MATERIALS AND SAMPLE PREPARATION

In this section, the sample preparation for this work is presented. The mortar sample is made in different thicknesses to observe the variation of curing time which may occur during the hydration process. Four samples with 1.1, 2.2, 3.3, and 4.4 cm thicknesses are prepared and fixed to one sample holder in order to be placed between the horn antennas. All the samples are prepared from constant ratios of cement, sand, and water. In Table 1, the outlined ratios of cement, sand, and water for the four prepared samples are listed. The mortar samples cross size is fixed to 28 cm × 28 cm × 4.4 cm. The volume of water is set to 350 g for the mortar sample.

Table 1. Table 1 illustrates the ratios of sand, cement and water for four different thicknesses of mortar sample.

Thickness (cm)	Sand (g)	Cement (g)	Water (g)
1.1	1000	500	350
2.2	1000	500	350
3.3	1000	500	350
4.4	1000	500	350
Total	4000	2000	1400

3. RESULTS AND VALIDATION

3.1. Measurement Setup

In this section, the prepared samples are measured using a free space technique by conducting two horn antennas where the sample is at the model space. The reflection and transmission coefficients in terms of S-parameters spectra are evaluated. The S-parameters, magnitude of the transmission, and reflection coefficients within the frequency band from 8 GHz to 32 GHz are obtained using two ports Anritsu 37369D Vector Network Analyzer 40 MHz–40 GHz OPT 10a. The S-parameters measurements are represented by S_{11} and S_{21}, magnitude of reflection and transmission coefficients, respectively. The two full ports calibration is applied to eliminate the mismatch and phase shit errors in S_{11} and S_{21} measurements. The full two ports calibration involves the measurements of open, short, and 50 Ω load standards for both ports, followed by a through standard, simply achieved by directly connecting the two supporting cables for each port. In the curing time measurements, the mortar sample is placed (horizontally) in between a pair of lens horn antennas to avoid any diffraction from the edges of the sample [9]. For this, the sample area is chosen to be of size $28 \times 28\,\text{cm}^2$. The sample holder is located in the middle of two antennas with 10 cm gap between receiver/transmitter antennas to the sample holder at the far-field scattering [5]. The used models of the horn antennas are 18820-FA with nominal gain of 25 dBi, and VSWR is less than 2.5, when, 1.515 cm aperture diameter. These antennas are manufactured and designed by Flann Microwave Limited.

Now, the dielectric properties in terms of relative permittivity, real part, and loss factor, imaginary part, measurements are obtained using a commercial probe sensor, Open Ended Coaxial Probe HP85070B, with frequency band of interest at room temperature (27°C). The used VNA is a 2-port Precision Network Analyzer with power range from −30 dBm to −15 dBm at operating temperature of −40°C to 200°C. As a manufacturer recommendation, there are three references of the dielectric for the calibration process at the open-ended coaxial cable aperture, represented by air, shorting block, and water, connected to VNA. In the curing time measurements, each thickness of the mortar structure is measured every 5 hours after the casting process until the mortar obtained totally dry condition after 71 hours [1]. Therefore, it is found that the dielectric constant and loss factor for each mortar sample depend on the state of drying process. However, the dielectric properties in this work are presented for dried samples under the ordinary room temperature. Figure 1 shows a block diagram for measuring the dielectric properties of mortar sample.

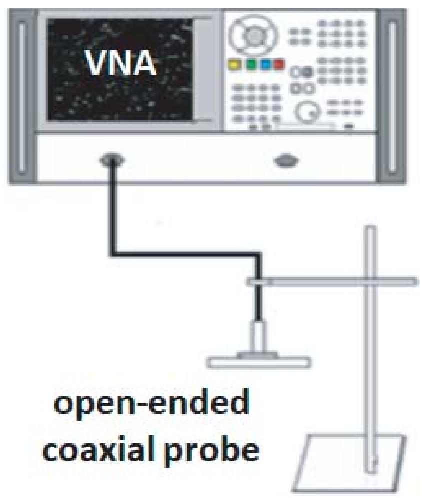

Figure 1. VNA with open-ended coaxial probe for measuring the dielectric properties.

3.2. Results and Discussion

Figure 2 shows the relationship between the dielectric constant and loss factor for mortar structure with different thicknesses for the frequency range from 8 GHz up to 32 GHz while the mean values are listed in Table 2. It is found that thicker samples exhibit higher values of both dielectric constant and loss factor due to the increase of skin depth effects of the material density [10]. The mortar sample is made of 33.33% cement and 66.66% sand; however, samples with thickness above 4.4 cm are not shown as the dielectric constant and loss factor profiles overlapped with mean values equal to 2.23435 and 0.288226 dielectric constant and loss factor, respectively.

Now, to realize curing time conditions effects on the dielectric properties of prepared samples, water dielectric properties are discussed firstly. Figure 3 illustrates the variation of the dielectric constant and

Table 2. Mean values of the dielectric constant and loss factor at different thicknesses of mortar structure.

Thickness, d	**The Mean Values**	
	Dielectric Constant (ε')	**Loss Factor (ε'')**
1.1 cm	1.914285	0.190155
2.2 cm	2.056326	0.19202
3.3 cm	2.110832	0.189014
4.4 cm	2.23435	0.288226

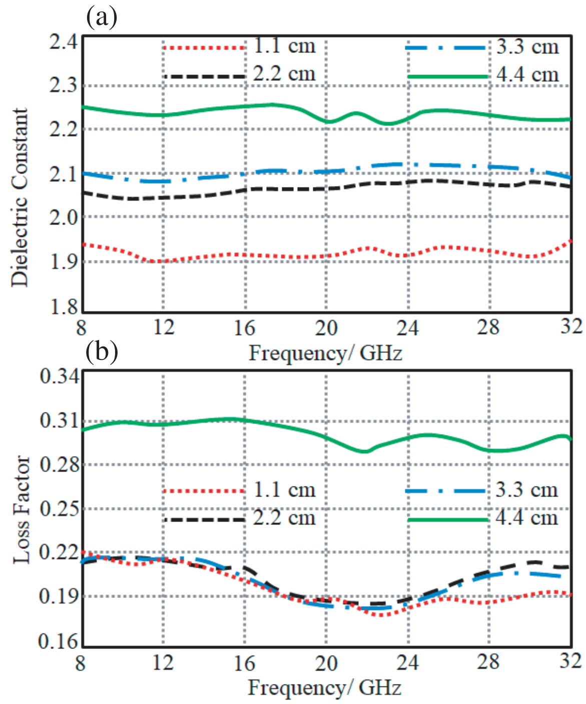

Figure 2. (a) Dielectric constant and (b) loss factor for mortar structure.

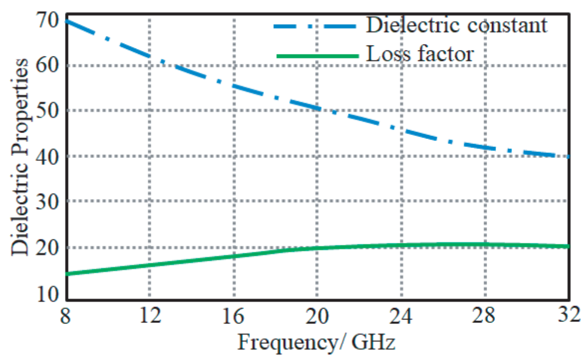

Figure 3. The dielectric constant and loss factor of water.

the loss factor of water at the same frequency range. It is observed that the dielectric constant is much higher at the lower frequencies. In contrast, the loss factor increases rapidly with the frequency increase to be an almost constant value after 17.5 GHz. Such an observation is called the relaxation frequency which is an important observation that represents the maximum wave attenuation during the frequency band of interest [11].

3.3. Results Validation

For validation, a K-band waveguide of two ports is used with the VNA to measure S-parameters of the prepared samples. Therefore, the considered mortar structures are prepared again but with a different area to suite the internal sectional area of the used waveguide. Later, CSTMWS software package [12] is invoked to realize the validation for the obtained results from measurements. Nicolson-Rose Weir (NRW) technique is investigated for bulk material characterizations [13] to realize more flexibility and deep penetration by S-parameters measurements. The measured complex permittivity is used as the initial guess to determine the S-parameters in CSTMWS simulations at the K-band.

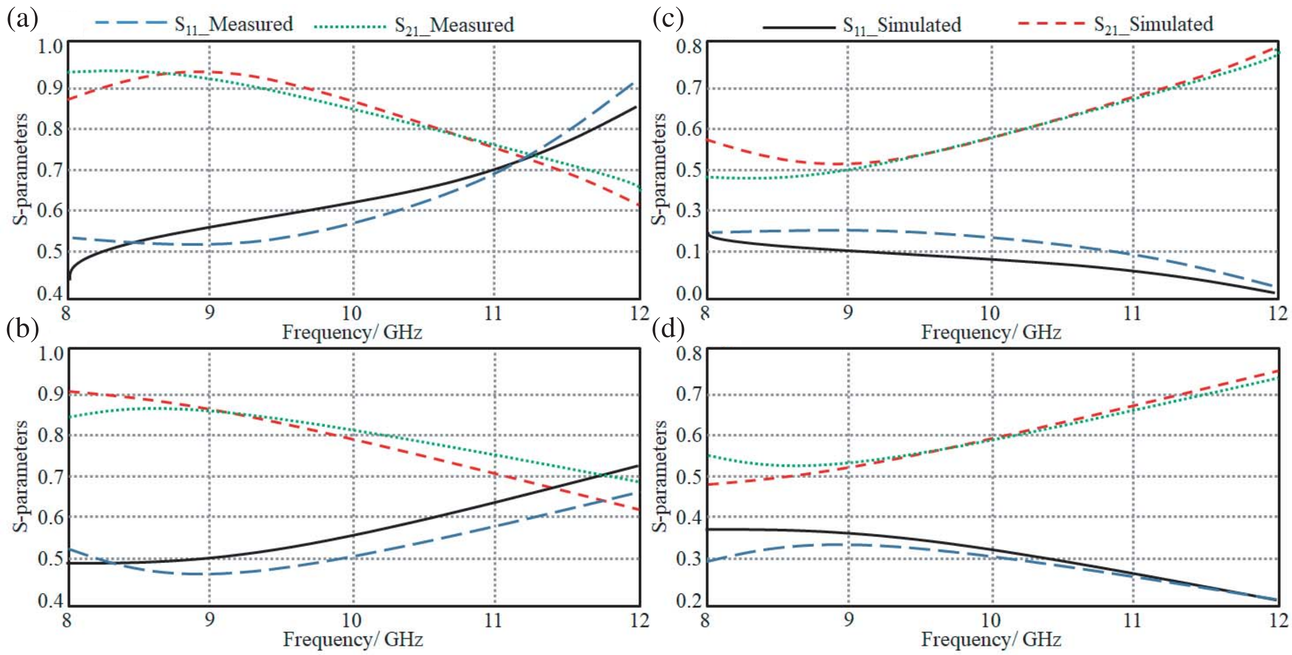

Figure 4. S-parameters measurements and simulated results at different thickness: (a) 1.1, (b) 2.2, (c) 3.3, and (d) 4.4.

The measured S-parameters based on NRW technique are compared to those obtained from CSTMWS simulations. Figure 4 shows an excellent matching between the measured and simulated S-parameters in terms of S_{21} and S_{11} magnitudes spectra with insignificant errors that could be attributed to undesirable diffractions/reflections from the edges of the sample [14]. The obtained results reveal excellent agreements validating the obtained results from the previous section.

3.4. Curing Time Effects on the Dielectric Properties and S-Parameters

The measurements of the magnitude of reflection and transmission coefficients (S_{11}, S_{21}) of the mortar structure at different thicknesses are conducted at the relaxation frequency (17.5 GHz) in ordinary room conditions. Figure 5 illustrates the relationship between S_{11} and S_{21} magnitude variations with respect to the curing time for the prepared samples. When the period of curing increases, the amount of free water in mortar decreases attributed to the procedure of cement hydration and evaporation [15]. The water changes from free to an absorbed state, which reduces ionic polarization and conductivity due to decreases in ion production [16]. Additionally, the pore sizes become very small, in consequence making it difficult for the movement of free water remaining in mortar [13]. The reflection coefficient in Figure 5(a) is a strong function of the dielectric constant of water [16]. It can be clearly observed from the dielectric properties of water that the dielectric constant of water values was much higher at the lower frequencies [14]. In contrast, the loss factor increased rapidly with frequency but reaches almost a constant value above 15 GHz due to the presence of ionic activity at the vicinity of the relaxation frequency. The latter could be the main reason of the instabilities of the profile of reflection coefficient with the existence of crisscrossing lines. Figure 5(a) also shows the rapid decrease around the first 40 hours. The decreasing rate becomes small after 40 hours of curing time as a result of the evaporation of free water from the mortar structure and the hydration process. Figure 5(b) shows the relationship between transmission coefficient (S_{21}) and curing time at different thicknesses. Generally, the S_{21} values increased with increasing curing time and decreased with increasing the thickness of mortar structure. The results of the measured S_{21} also showed a rapid increase after several hours of the curing time, due to the desiccation of water from the whole mortar as an effect of a progressive drying. Reduction in S_{21} values at 17.5 GHz was due to the high absorption of water which coincides with its relaxation

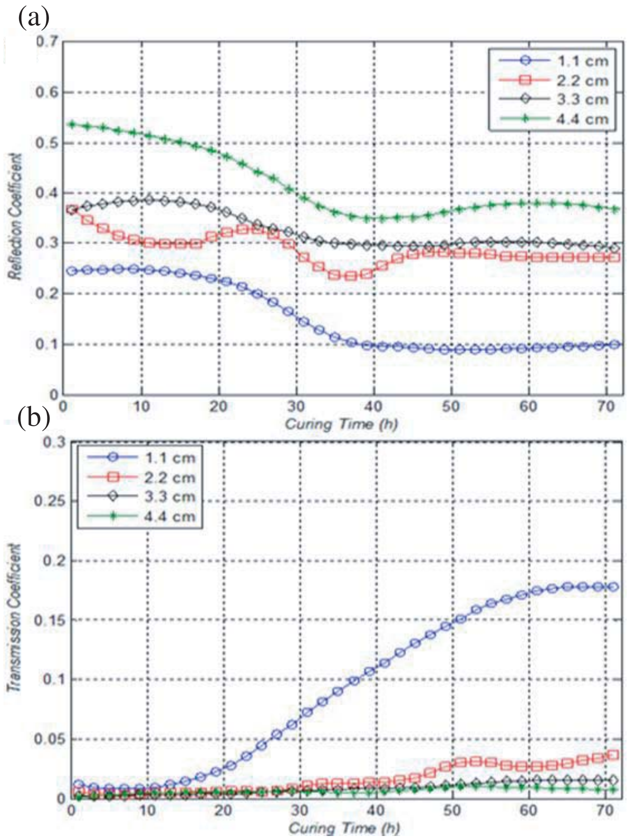

Figure 5. Curing time variation with respect to (a) reflection coefficient and (b) transmission coefficient at 17.5 GHz.

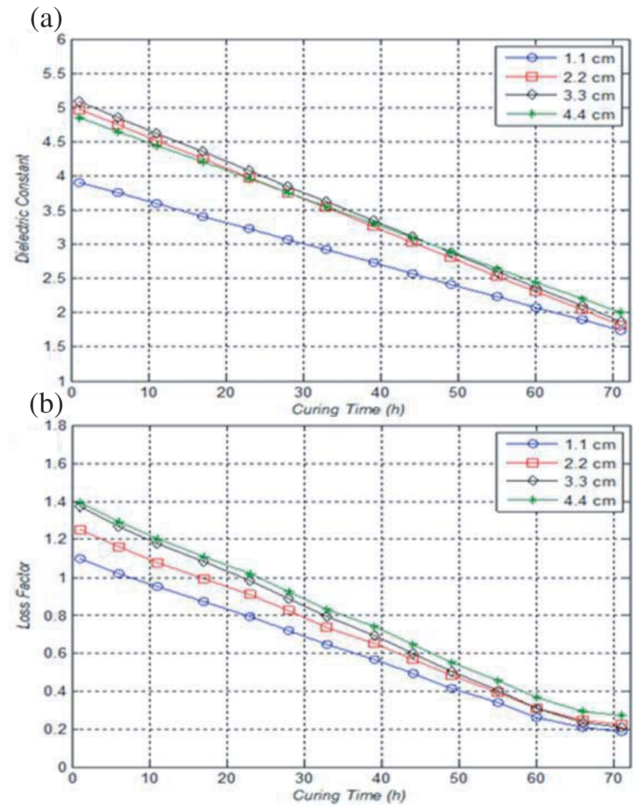

Figure 6. Curing time variation with respect to (a) dielectric constant and (b) loss factor at 17.5 GHz.

frequency.

The measurements of the dielectric properties using an open ended coaxial probe of the mortar structure at different thicknesses are continuously conducted during the 71 hours of curing period. It can be clearly seen from Figure 6(a) that the dielectric constant decreased with increasing curing time due to evaporation of the water. In Figure 6(b), the loss factor decreased with curing time because the loss factor of the dielectric properties principally depends on the transmission coefficient described by S_{21}. The mortar dielectric properties decrease with the increasing water content evaporation. It can be clearly seen that the high loss factor values corresponded to higher water ratio before hydration [13]. It is recognized that the higher porosity corresponds to higher water content ratio [12]. It should be noted that higher relative rate of the loss factor corresponds to higher water content ratio [11]. The values of the dielectric constant and loss factor have good agreement with the frequency range at 17.5 GHz which is equal to the relaxation frequency of water.

4. CONCLUSION

The effects of different thicknesses of mortar structure, 1.1, 2.2, 3.3, and 4.4 cm, on the dielectric constant and loss factor are obtained. It is found that the minimum thickness of samples to have static values of dielectric constant and loss factor is 4.4 cm instead of 1.89 cm, when using the manufacturer's recommended equation. The dielectric constant and loss factor of a typical mortar mixture with 33.33% cement and 66.66% sand were found to be 2.23435 and 0.288226, respectively. The variation of curing time with the dielectric properties and the S-parameters using open-ended coaxial probe and free space technique was distinguished during 71 hours. By monitoring the curing time, it was found that the reduction in transmission coefficient values at 17.5 GHz was due to the high absorption of water coinciding with its relaxation frequency.

ACKNOWLEDGMENT

The authors would like to thank the ministry of higher education in Malaysia for supporting this work. Special thanks also given to the members of the RF & Microwave Instrumentation laboratory, Department of Physics, Universti Putra Malaysia.

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