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Determination of Dielectric Property Profile in Cement-Based Materials Using Microwave Reflection and Transmission Properties

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Abstract *– Microwave characterization methods are effective means for evaluating dielectric properties of materials and correlating them to their important physical, chemical and mechanical properties. For characterization purposes most materials are considered homogeneous and the measurement of their dielectric properties is fairly straightforward. However, certain materials may be considered inhomogeneous in such a way that their dielectric properties vary in a preferred direction within the material. To evaluate the dielectric property profile of these materials an electromagnetic model is necessary that can be used along with their measured reflection and transmission properties. This paper presents the development of such a model which is subsequently used to determine the dielectric property profile in mortar samples exposed to cyclical ingress of salt solution.*

I. INTRODUCTION

Microwave dielectric characterization methods are effective means for evaluating dielectric properties of materials and relating them to their important physical, chemical and mechanical properties [1-4]. Microwave dielectric material characterization approaches are quite varied in methodology depending on the material type (solid, liquid, etc.), its geometry of the material, the desired measurement accuracy, and the measurement environment (on-line vs. laboratory) [5]. Most materials are considered to be homogeneous and the measurement of their dielectric properties is fairly straightforward. However, there are cases where a material is considered to be inhomogeneous. Additionally, their dielectric properties may be relatively constant along two directions (within the material) and vary along the third. These materials are categorized as those possessing a dielectric property profile or that their dielectric properties possess a gradient of change along a certain direction/axis. Such materials may be encountered in many practical environments, for example moisture or chemical permeation into dielectric materials such as fiberglass or concrete storage tank walls and cyclical salt ingress into concrete bridge decks, piers and columns. As it relates to the ongoing research activities of the authors, the problem of evaluating cyclical chloride/salt ingress in cement-based materials is under consideration here, since chloride intrusion is the primary cause of corrosion in steel reinforcing bars [6]. Microwave nondestructive testing techniques have been successfully used to detect the intrusion of chlorides into these materials [7]. However, a thorough modeling effort is also necessary to evaluate the various aspects of such processes.

Consequently, a 10 cm-long mortar sample with a water-to-cement ratio (*w/c*) of 0.45 and sand-to-cement ratio (*s/c*) of 1.5 was exposed to a NaCl solution with a salinity of 5% for 20 cycles. The sample was produced so that it could tightly fit inside of a rectangular waveguide sample-holder, at S-band (2.6-3.95 GHz). The sample was exposed in a particular fashion in order to result in a profile of salt solution ingress along its length [7-8]. After each salt solution exposure the mortar sample was oven-dried so that a consistent moisture content was obtained throughout the sample. Subsequently, the calibrated microwave reflection and transmission properties of the sample were measured using a vector network analyzer in conjunction with a two-port completely-filled waveguide technique as shown in Figure 1.

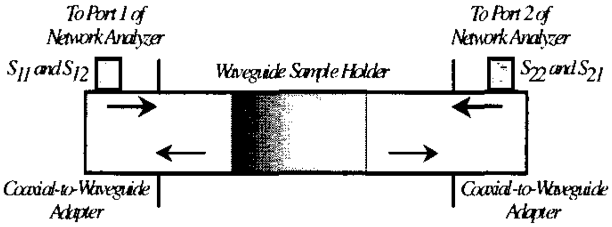

Fig 1. Microwave measurement apparatus using a vector network analyzer.

To understand these measurements and be able to retrieve the dielectric property profile of the sample after each soaking and drying cycle, an electromagnetic model was also developed. The model simulates the microwave reflection and transmission properties of a dielectric material when encased in a rectangular waveguide sample-holder (as shown in Fig. 1) and possessing a varying dielectric property profile along its length. The electromagnetic model was developed using two different approaches, namely; a discrete/multi-layered and a continuous approach [9-10]. Subsequently, an iterative back-calculation model was developed in

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conjunction with the continuous model for recalculating the dielectric property profile of the mortar sample from the measured reflection and transmission coefficient properties [7].

II. THE ITERATIVE BACK-CALCULATION APPROACH/MODEL

The iterative back-calculation model determines the dielectric property profile based on the measured reflection and transmission properties. The approach is based on determining the effective propagation constant of the mortar sample, given by Equation (1).

$$\gamma_{eff}(f) = j\sqrt{\omega^2\mu_0\varepsilon_0\varepsilon_{eff} - \left(\frac{p\pi}{a}\right)^2 - \left(\frac{q\pi}{b}\right)^2} \tag{1}$$

where, p and q determine the mode of operation, for dominant mode $p = 1$ and $q = 0$, and a and b are the side dimensions of the rectangular waveguide. μ_0 and ε_0 are the permeability and permittivity of free-space, respectively and ε_{eff} is the effective dielectric property (relative-to-air) determined by using a previously developed method [11]. ε_{eff}, represent the dielectric properties of the sample (with dielectric property profile) as if it were to possess a uniform dielectric property along its length.

If $\varepsilon(x)$ is the sought for relative dielectric property profile (whose effective dielectric properties is ε_{eff}) along the length of the sample (a function of length), then the effective propagation constant can also be calculated by using Equation (2).

$$\gamma(f) = \frac{\left(\int_0^d j\sqrt{\omega^2\mu_0\varepsilon_0\varepsilon(x) - \left(\frac{p\pi}{a}\right)^2 - \left(\frac{q\pi}{b}\right)^2}\right)dx}{d} \tag{2}$$

where, d is the length of the sample and x is the direction along the length [7,10].

To solve for $\varepsilon(x)$ a general quadratic function was assumed, given by Equation (3).

$$\varepsilon(x) = \frac{1}{P_0x^2 + Q_0x + R_0} - \frac{j}{P_1x^2 + Q_1x + R_1} \tag{3}$$

where, $P_0, Q_0, R_0, P_1, Q_1, R_1$ are the coefficients of the general quadratic function used. This function is general so that any type of dielectric properties can be simulated by it. Using an iterative process the effective propagation constant was computed using Equation (2). The set of coefficients, which resulted in minimum error between Equations (1) and (2), were then used to recalculate the dielectric property profile of the sample for every cycle. These dielectric property profiles were then used to simulate the microwave reflection and transmission properties using the discrete and the continuous models [7]. By comparing the simulated and the measured reflection and transmission properties the validity of the dielectric property profile can be verified, i.e. a match between the simulation and the measurements implies that the actual dielectric property profile is determined.

The above procedure always results in two solutions, one which is the actual dielectric property profile and the other which is the profile whose coefficients of x and x^2 are close to zero (i.e., the profile is a constant which is equal to the effective dielectric property). Since the mortar sample is soaked in such a way as to generate a dielectric property profile along its length the second solution is invalid.

III. SIMULATION RESULTS

The iterative back-calculation model was applied to various measurement cycles. Figures 2-13 show the simulated (using the continuous model) and the measured microwave reflection and transmission properties of the mortar sample at S-Band (2.6-3.95 GHz) for cycles 0, 6 and 20.

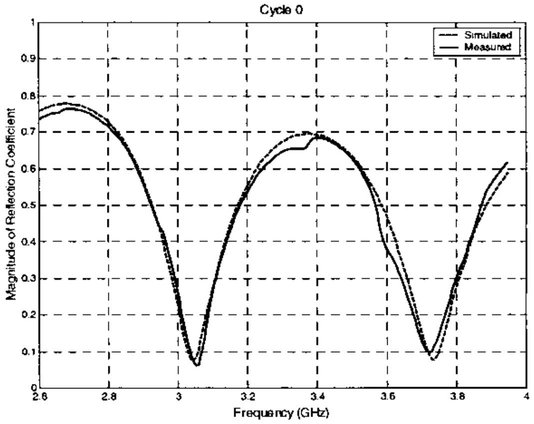

Fig 2. Magnitude of reflection coefficient.

The results clearly show good agreement between the simulated and the measured reflection and transmission coefficients. It is important to note that all four parameters (i.e., magnitudes and phases of reflection and transmission coefficients) were closely simulated using this procedure.

Figures 14 and 15 show the resulting calculated dielectric property profiles as a function of sample length for cycles 0, 6 and 20. These results also show that the back calculation algorithm was also successful in determining the dielectric property profile of the sample as a function of soaking and drying cycles.

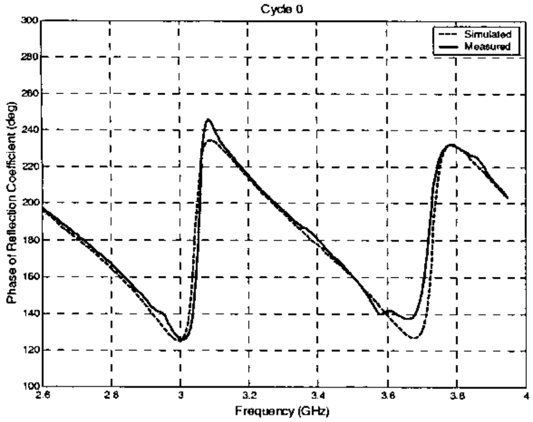

Fig 3. Phase of reflection coefficient.

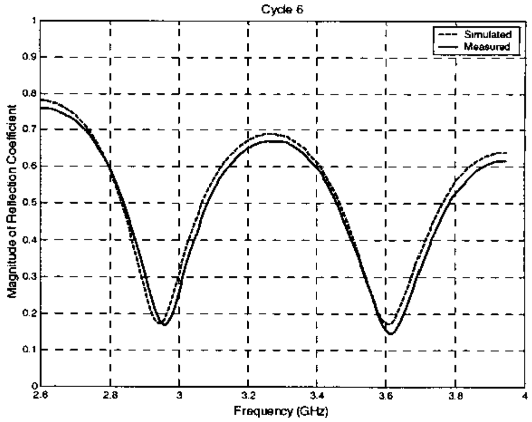

Fig 6. Magnitude of reflection coefficient.

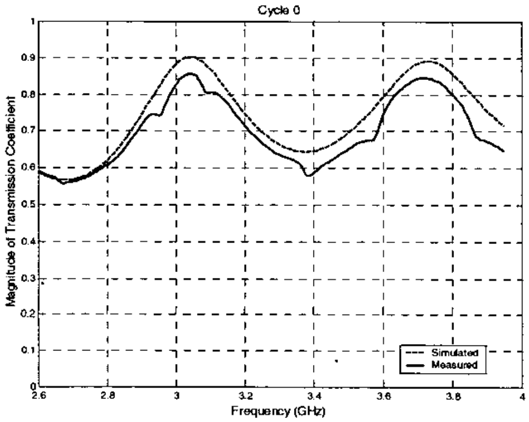

Fig 4. Magnitude of transmission coefficient.

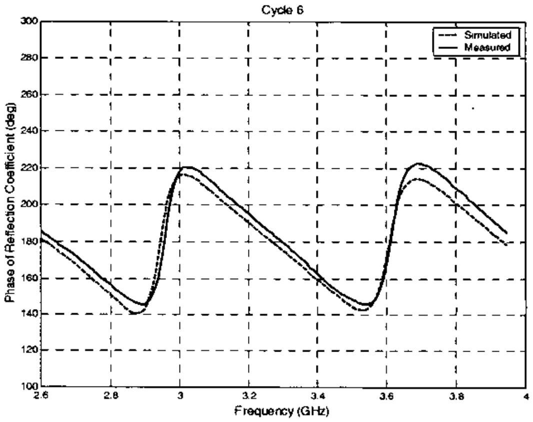

Fig 7. Phase of reflection coefficient.

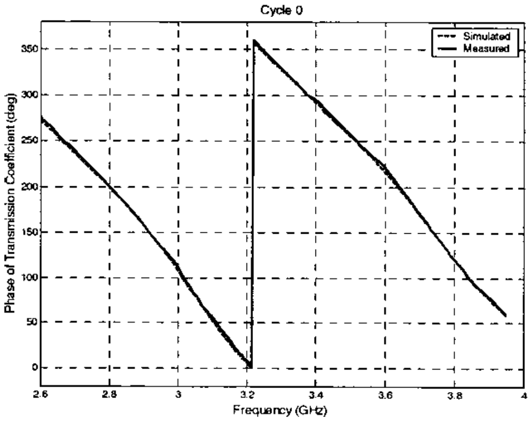

Fig 5. Phase of transmission coefficient.

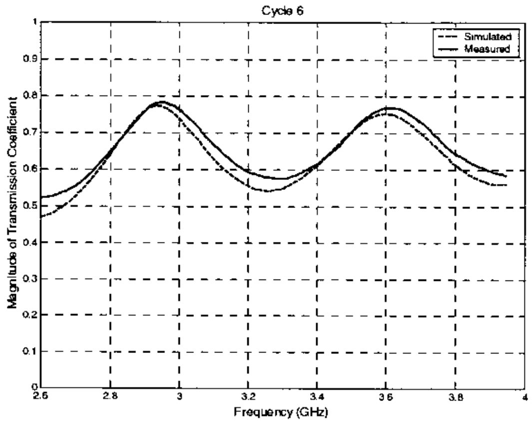

Fig 8. Magnitude of transmission coefficient.

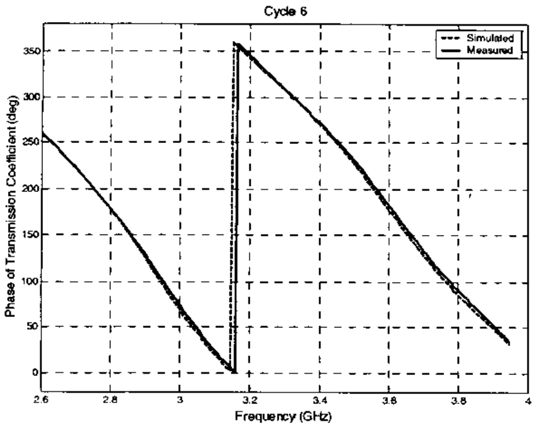

Fig 9. Phase of transmission coefficient.

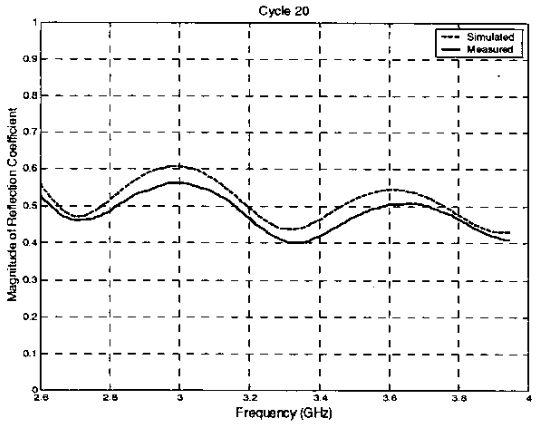

Fig 10. Magnitude of reflection coefficient.

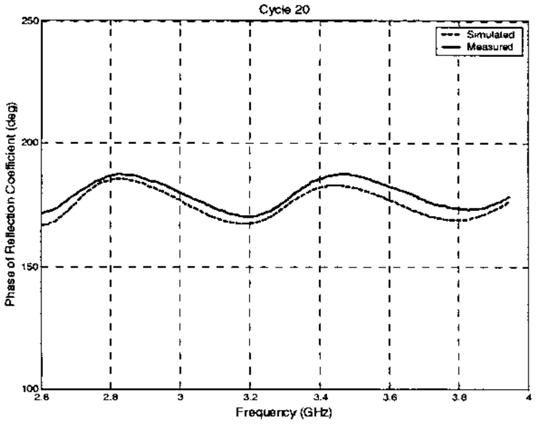

Fig 11. Phase of reflection coefficient.

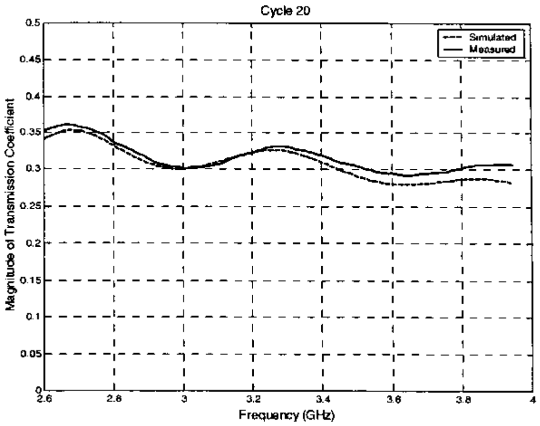

Fig 12. Magnitude of transmission coefficient.

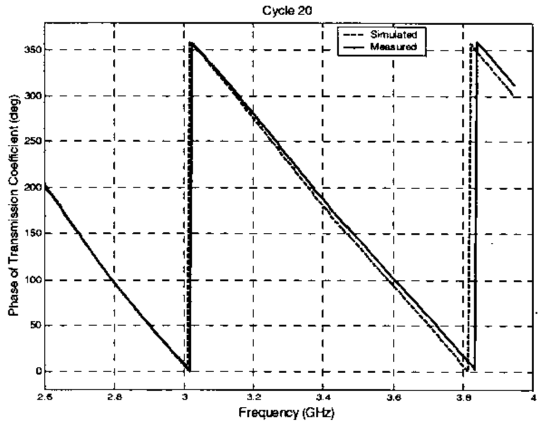

Fig 13. Phase of transmission coefficient.

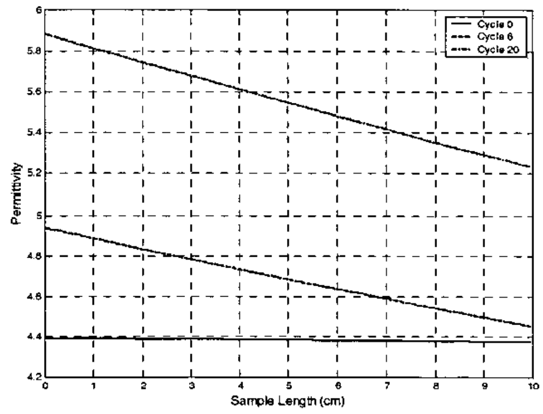

Fig 14. Permittivity profile as a function of sample length.

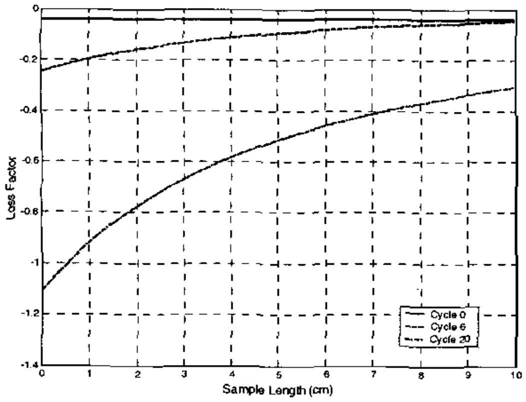

Fig 15. Loss factor profile as a function of sample length.

Upon examining Figures 13 and 14 several interesting points are noticed. The cycle 0 results show a constant dielectric property profile, implying a uniform dielectric property profile in the sample, i.e., the sample was homogenous before exposing it to the salt solution, as expected. The results also show that there is a progressive increase in the dielectric property profiles as a function of exposure cycles, also as expected. Now that the dielectric property profiles are determined they can be used to determine the sought-after gradient of salt ingress (i.e., characterization of the distribution of additional solid products in the sample after each soaking cycle) within the sample using a dielectric mixing model.

A dielectric mixing model relates the dielectric properties and the volume fraction of the individual constituents of a mixture to the dielectric constant of the mixture [12-13]. In this investigation the mixture constitutes of mortar, air (porosity) and newly formed (additional) solid products resulting from salt solution ingress. The porosity of the mortar sample was measured to be around 25% [7]. This value is consistent with those reported elsewhere [14-15]. By knowing the essential parameters such as dielectric property profile and the porosity of the sample the additional solid product distribution or profile was calculated using a general three phase dielectric mixing model [7,12]. The calculated additional solid product profiles for cycles 0, 6 and 20 are shown in Figure 16.

From Figure 16 it can be seen that the additional solid product distribution in the sample for cycle 0 is almost zero, as expected. It can also be seen that as a function increasing number of cycles there is a progressive increase in the amount of additional solid products in the sample, also as expected.

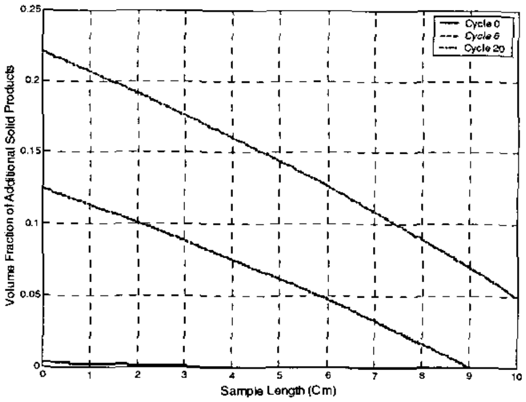

Fig 16. Additional solid product distribution as a function of sample length.

IV. CONCLUSION

Dielectric materials whose dielectric properties possess a certain profile are increasingly of interest in various applications. In this investigation the microwave reflection and transmission properties of a mortar sample possessing a gradient of dielectric properties along its length, obtained by cyclical exposure to salt solution, were measured showing that microwave techniques can successfully detect the changes in the dielectric properties of the sample. A continuous electromagnetic model was also developed to simulate the measurement results and back calculate the dielectric profile. The simulation results showed that the iterative back-calculation model was successful in determining the dielectric property profile of the mortar sample. These dielectric property profiles were then used to compute the sought-after gradient of salt ingress (i.e., as measured by the formation of additional solid products) within the sample by using a dielectric mixing model.

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