01 May 2003

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Recommended Citation

S. Peer et al., "Electromagnetic Modeling of Saltwater Ingress in Mortar at Microwave Frequencies," *Proceedings of the 20th IEEE Instrumentation and Measurement Technology Conference (2003, Vail, CO)*, vol. 1, pp. 509-512, Institute of Electrical and Electronics Engineers (IEEE), May 2003.
The definitive version is available at https://doi.org/10.1109/IMTC.2003.1208210

IMTC 2003 – Instrumentation and Measurement
Technology Conference
Vail, CO, USA, 20-22 May 2003

Electromagnetic Modeling of Saltwater Ingress in Mortar at Microwave Frequencies

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Abstract* - Corrosion of reinforcing steel is a major cause of damage and deterioration in reinforced concrete structures. Therefore, as the presence of a sufficient concentration of chloride ions can lead to the onset of corrosion in embedded steel, it is of utmost importance to be able to determine the free salt content and its distribution in these materials. Moreover, it is important to obtain this information nondestructively. Previous investigations have shown the capability of near-field microwave nondestructive evaluation methods, using open-ended rectangular waveguide probes, to evaluate many important properties of cement-based materials. In this investigation, the temporal microwave reflection properties of a mortar cube, subjected to cycles of wetting in a saltwater bath with a salinity of 2.8% and drying were measured at 3 GHz and 10 GHz using open-ended rectangular waveguides for several cycles, each lasting about 35 days. A semi-empirical electromagnetic model was then developed, representing the cube as a stratified structure with a dielectric constant profile to simulate the measured reflection properties. The issue of representing a continuous media as a stratified structure was also explored. The simulated and the measured results at both frequencies, and for all cycles were in good agreement. Subsequently, the volumetric free salt distribution, left in the cube, was also calculated. This paper presents a brief description of the model and its results at 3 GHz for the first cycle.

I. INTRODUCTION

Presence of free chloride ions in concrete is one of the major causes of steel corrosion in reinforced concrete structures. When steel is encased in concrete, a protective passive film forms on the steel surface due to the high pH of the concrete. This film protects the steel from corrosion. However, the presence of a sufficient concentration of chloride ions near the steel in reinforced concrete can cause this protective film to be destroyed. When moisture and oxygen are present in the concrete, the steel will corrode through an electrochemical process [1]. Chloride ions exist in concrete in two forms — bound and free. Only the free chloride ions, those dissolved in the pore solution, participate in the corrosion process.

The development of a reliable test method for *in-situ* measurement of the chloride ion penetration in in-service concrete would be invaluable to the concrete and construction industry. Near-field microwave nondestructive techniques have been used to interrogate a wide variety of cement-based materials for their important physical and structural properties [2-3]. This paper outlines the development of a semi-empirical electromagnetic model that can be employed to simulate the microwave reflection properties of a mortar cube cyclically exposed to salt solution with a salinity of 2.8 %.

II. EXPERIMENTAL APPROACH

An 8"x 8" x 8" mortar cube having a water-to-cement ratio (*w/c*) of 0.50 and sand-to-cement ratio (*s/c*) of 2.5 was prepared and cured for X days. Subsequently, it was soaked in a NaCl solution with a salinity of 2.8% for 24 hours. Subsequent to removing from the bath, the microwave reflection properties of the cube at two different frequency bands (S-band and X-band) were measured on a daily basis for the next 35 days using open-ended rectangular waveguide probes, in conjunction with an HP8510C vector network analyzer. This procedure was repeated for three such soaking and measurement cycles. Concurrently, the mass of the cube was measured daily to be used as physical data to be incorporated into an electromagnetic model. The measured results and the modeling analyses were performed for two specific frequencies of 3 GHz (S-band) and 10 GHz (X-band), representing each frequency band.

III. EXPERIMENTAL RESULTS

Figure 1 shows the measured reflection properties of the cube at 3 GHz. The results indicate that the magnitude of reflection properties gradually decreases while the phase of reflection coefficient increases as a function of days. This behavior is primarily as a result of evaporation of water from the cube. A complete discussion of the experimental results is given in reference [4]. However, one important aspect regarding the reflection properties is a distinct dip occurs in the phase of reflection coefficient during the first few days of the cycle, while the measured phases gradually increases as a function of days beyond this point. The gradual increase (after the first few days) could be primarily attributed to the evaporation of water. However, the dip is indicative of an additional phenomenon that is occurring within the cube and as will be proposed later, may relate to the movement of saltwater within it.

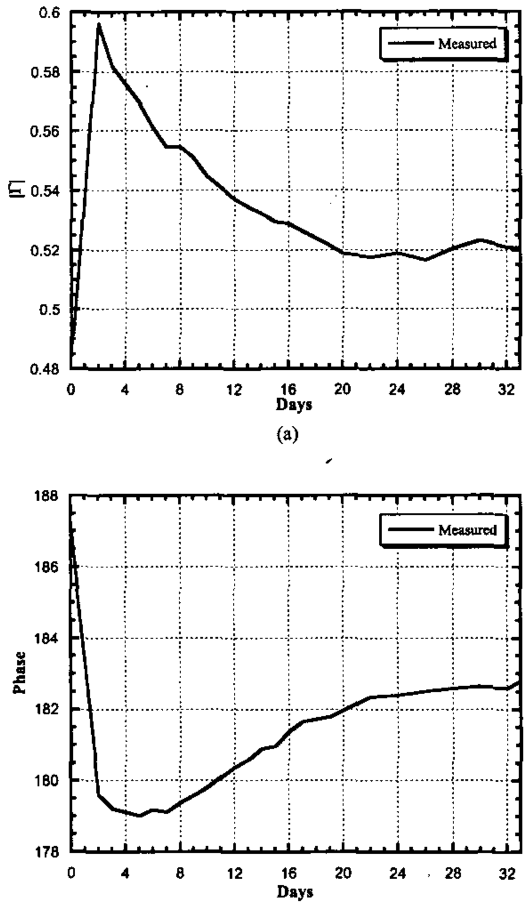

Fig. 1. Reflection properties at 3 GHz, (a) magnitude and (b) phase.

IV.MODELING PROCEDURE

The reflection properties of the mortar cube are the result of various phenomena that occur within it. (Due to the age of the cube, cement hydration can be largely neglected and analysis can focus on the effect of the environmental exposure). To obtain a clear understanding about these phenomena, a modeling process was initiated. The primary requirement for the development of such a model is the conceptualization of the temporal state of the cubes as well as the various changes that occur within it. As water evaporates from the cube, it results in a non-uniform distribution of saltwater within the cube. Although this distribution is continuous, for modeling purposes the mortar cube can be analyzed as a collection of discrete layers. The representation of a continuous media as discrete layers can be justified through a sensitivity analysis of the model for various thicknesses.

As water evaporates from the cube and various salts reach their saturation concentration in localized regions within the sample, salt crystals precipitate out in the preexisting pores and cracks in the mortar. Thus, the soaked mortar cube can be represented as a multi-phase dielectric mixture, where the host material comprises of hardened cement paste and sand while pore solution (with increasing salinity), salt crystals and air (pores and cracks) constitute the inclusions. In addition, existing products of cement hydration may chemically combine with the ingressing salt, binding it, and forming new products. It has been shown that the water content distribution within a mortar cube can be represented with Rayleigh-like distribution functions [5]. Equation (1) shows the distribution function that represents the distribution of soluble salt (ingressing into the cube from the saltwater bath) within the cube as a function of days. The only physical data that is utilized by the model is the daily mass of the cube, where the integral of the distribution for any day should be equal to the mass of the cube for that day. However, the parameters of the distribution that determine its shape have to be determined from a trial and error process. Based on this

$$SWD(t)=k_4\left[\frac{t}{k_1}\right]^{k_2} e^{\left[-k_3\left(\frac{t}{k_1}\right)^{k_2}\right]} \qquad (gm/mm) \qquad (1)$$

distribution, the effective dielectric properties of each layer could then be calculated by using a multi-phase dielectric mixing formula [6]. The factors that serve as input to the dielectric mixing formula are the dielectric properties of each of the phases (both host and inclusion) as well as their respective volume fractions. In the context of the modeling process the volume fractions of hardened cement paste and sand remain fixed while that of air varies due to the inclusions replacing it, as a function of days. The effective dielectric properties of each layer for the entire cycle was calculated after taking into account the conductivity of each layer [7]. It should be noted that the conductivity (for any day) varies from layer to layer owing to the presence of varying amounts of salt dissolved in the pore solution and the varying amounts of salt precipitated in the pores, as is suggested by the saltwater distribution within the cube. In addition to the free salt (present both dissolved in solution and as salt crystals), it is also proposed that with the passage of days, the presence of bound salt becomes significant enough to be considered in the model. In the context of the modeling process, it is proposed that the effect of bound salt be treated so as to cause a decrease in the volume content of the free salt, thereby causing a corresponding decrease in the conductivity. Although the presence of bound salt has not been explicitly represented in the model, its effect has been considered (as will be discussed later). Thus, the conductivity of each layer was first calculated based on the amount of free salt present in that particular layer after which, the dielectric mixing formula was invoked to calculate the effective dielectric properties. Subsequently, a multi-layered formulation was employed to simulate the reflection properties of the cube for each day of the cycle [9].

V. MODELING RESULTS

Figure 2 shows the simulation results obtained from the model at S-band (3 GHz) for several cases of thickness of each layer. The results indicate that for the cases where the thickness of each layer is less than 2 mm, there is no appreciable change in the simulation results. It can therefore be assumed that if the thickness of the layers is small enough, there would be negligible difference between the continuous and discrete case and hence a discrete case would suffice for modeling purposes. In the present model, the thickness of each layer was maintained as 1 mm. The results also show very good agreement between the simulated and measured

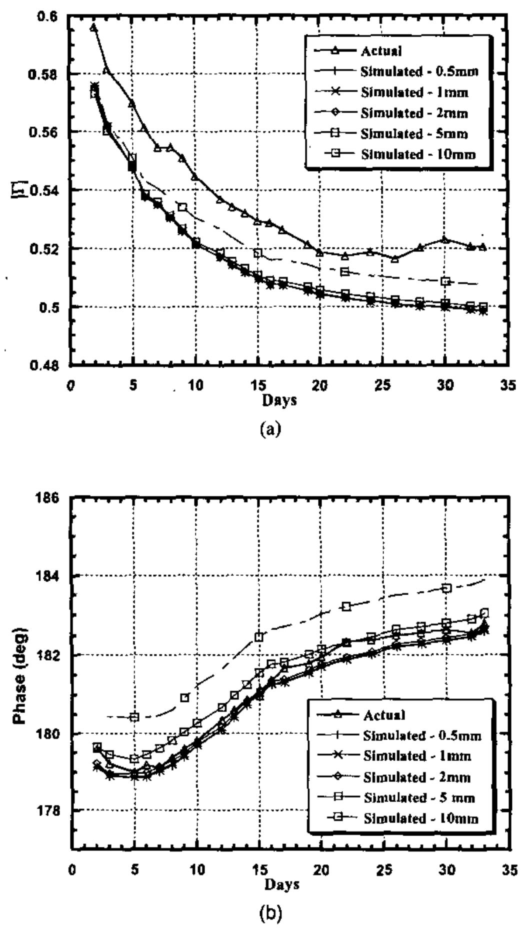

Fig. 2. Simulation results at 3 GHz, (a) magnitude and (b) phase.

reflection properties, for smaller thickness of the layers. Similar results were obtained for cycles 2 and 3.

Figure 3 shows the free salt distribution for several days of cycle 1 obtained from the modeling process. The results show several important phenomena. The first measurement, corresponding to day one is made 24 hours after removing the cube from the saltwater bath. During this time, it is expected

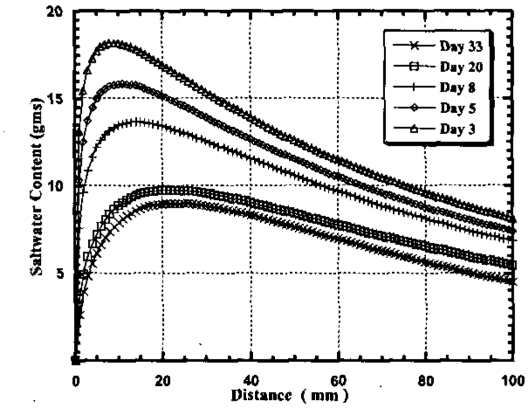

Fig 3. Free salt Distribution.

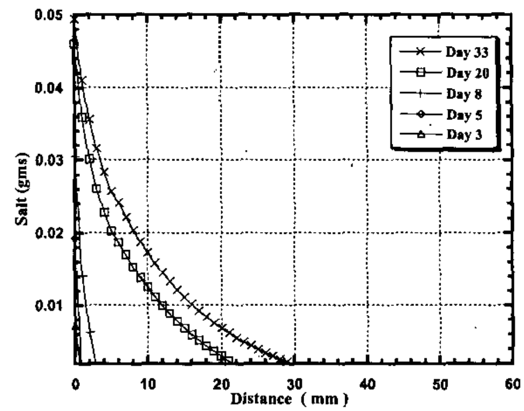

Fig 4. Crystalline salt Distribution.

that any water immediately at the surface has evaporated. The curves representing the free salt distribution indicate this phenomenon. Additionally, they also show that the free salt distribution rapidly increases as a function of distance into the cube. A comparison of the distribution curves shows that as the days progress there is a variation in (a) general shape of the distribution and (b) position at which the peak content of salt occurs. It was this dynamic nature of the distribution curves that allowed the model to accurately simulate the dip in the phase of reflection properties. Once taken out of the bath, water evaporates from the cube. As the evaporation process continues, the salinity of the solution left behind in the cube increases. After reaching a certain salinity level, the free salt in solution now begins to precipitate or crystallize. Several values were employed in the model to obtain a reasonable approximation of this salinity level. It was observed that the model was capable of simulating the reflection properties most accurately when the maximum salinity level was fixed at around 5-6%. Additionally, by setting a maximum level, the volume content of free salt that contributes to the salinity and hence the conductivity remains fixed. The remaining salt that would contribute to the salinity to be greater than the maximum salinity level can now be assumed to exist either as free salt crystals or bound within chloroaluminate products such as Friedel's salt. The dielectric properties of bound salt are expected to lie in the range between that of crystalline salt and dry mortar. That being the case, it is believed that the inclusion of bound salt explicitly in the model would have negligible effect on the simulated reflection properties. On the other hand, if the maximum salinity is not kept fixed, the total salt content would contribute to a significant increase in the salinity of each of the layers thereby causing significant change in the simulated reflection properties. In this manner, although the bound salt is not represented in the model as one of the additional inclusions in the dielectric mixing formula, its effect has been implicitly built into the model.

Figure 4 shows the resulting calculated profile of crystalline salt as a function of distance into the cube for corresponding days of cycle 1. As mentioned earlier, when the salinity in any layer reaches a certain threshold, it is assumed that free salt crystals appear in that layer. The salt profile as shown in Figure 4 indicates the distribution of crystalline salt as a function of days for several days of the cycle. The day one salt profile indicates that there is sufficient amount of water in each of the layers (except the first few layers) for the salt which has ingressed into the mortar to remain in solution. However, as the days of drying progress, water begins to evaporate and more and more salt begins to precipitate towards the core. This profile however, is based on the findings of a semi-empirical electromagnetic model and its accuracy can only be ascertained from an experimental verification of the results.

VI. DISCUSSION

The basic foundation and the results of a semi-empirical model, simulating the microwave reflection properties of mortar exposed to cyclical episodes of soaking in saltwater was presented. The simulation was carried out for several cases of thickness for each layer. The results indicate that as the layer thickness is reduced, the variation in the simulation results become negligible. Overall, the results of the model showed good agreement with the measured results. One of the outcomes of the model is the temporal free salt distribution and the gradient of free salt crystals inside the mortar cube for three successive soaking and drying cycles. The distribution functions followed a Rayleigh-like distribution and its specific parameters were determined empirically. Moreover, these distribution functions account for both evaporation of water and movement of water both toward the core of the cube and toward the surface of the cube. This aspect is evident from the change in the shape of the curves as well as the movement of the peaks as the days progress. It is this fact that enabled the model to correctly simulate the dip in the phase of reflection coefficient at 3 GHz during the first few days of the cycle.

ACKNOWLEDGEMENT

The material is based upon work supported by The National Science Foundation under Grant no. NSF CMS-0196158. Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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