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Comparison of Water and Saltwater Movement in Mortar Based on a Semiempirical Electromagnetic Model

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***Abstract*—The presence of chloride ions in steel-reinforced structures leads to the corrosion of the reinforcement thus compromising the integrity and strength of the structure. Thus, it is of great interest to nondestructively detect and evaluate free chloride content in concrete. To this end, an investigation was initiated where two mortar cubes were soaked in distilled water and saltwater solutions, respectively. Their temporal microwave reflection properties were measured using open-ended rectangular waveguides on a daily basis for three cycles, each lasting 35 days. Subsequently, a semiempirical electromagnetic model was developed to simulate the reflection properties of the cubes. The outcome of the model describes the water and saltwater distribution within the cubes. In addition, these distributions depict the manner by which the water and saltwater content temporally vary within the cubes. The presence of salt causes the saltwater distribution to be different than the water distribution in the respective cubes. This paper presents a comparison between the water and saltwater distributions obtained from this model. The results of such a comparison would then indicate the influence of salt on the mechanism of mass transport within the saltwater cube.**

***Index Terms*—Chloride, microwaves, moist substances, mortar, nondestructive testing.**

I. INTRODUCTION

EVALUATION of water and saltwater distribution and their temporal movement in cement-based materials is important for assessing cement hydration, curing, and, most importantly, long-term performance. During its manufacture, chloride ions can be introduced into concrete in several ways, such as when seawater or water with a high chloride concentration is used, when chloride-contaminated coarse or fine aggregates are used, or when chloride-containing admixtures are used. However, usually corrosion of reinforcing steel is caused by the ingress of chloride ions present in the surrounding environment of a concrete structure. Deicing salts, seawater, and chloride-contaminated aggregates are the primary sources of external chloride. When concrete is dry, chlorides can penetrate several millimeters in a few hours by the capillary draw of chloride-contaminated water into the concrete. When concrete is partially or fully saturated, chloride ions penetrate by diffusion through interconnected voids and cracks [1], [2].

Near-field microwave nondestructive evaluation methods have proven effective for evaluation of various mixture properties of cement-based materials including the detection of salt added to the mixing water and chloride ions entering these materials through exposure to saltwater solutions [3]–[10]. Electromagnetic modeling of the interaction of microwave signals with moist cement-based materials can provide the necessary insight for evaluating water and saltwater content distributions and their movement in these materials. To this end, the temporal microwave reflection properties of two mortar cubes, subjected to cycles of wetting and drying in water and saltwater, respectively, were measured using open-ended rectangular waveguides for three cycles, each lasting about 35 days. Prior to the development of the model to evaluate the saltwater content, an extensive study was first conducted on the distilled water-soaked cube. Subsequently, a semiempirical electromagnetic model, based on modeling the cube as a layered structure, was developed to simulate the measured reflection properties of this cube [11], [12]. Later, this model was modified to incorporate the additional influences caused by the presence of salt, thereby enabling the simulation the reflection properties of the saltwater-soaked cube [11]–[13]. The most important outcome of these modeling endeavors was obtaining the temporal behavior of water and saltwater distributions and hence their movement in these mortar cubes. This paper presents a comparison between the temporal water and saltwater distributions in these cubes, and their differences due to the presence of salt.

II. MEASUREMENT APPROACH

Two $8 \times 8 \times 8$ in mortar cubes having water-to-cement ratio (w/c) of 0.50 and sand-to-cement ratio (s/c) of 2.5 were produced using tap water and portland cement type I/II. The cubes were then placed in a hydration room for 24 hours and subsequently left at room temperature and low humidity for another ten months for the curing process to take place. Subsequently, they were submerged in a distilled water bath and a saltwater bath having a salinity of 2.8%, respectively, for 24 hours during each soaking cycle. The cubes were subsequently removed from the baths and left in the ambient conditions for 24 hours to allow excess water on the surface of the cube to evaporate. During the next 35 days daily microwave reflection properties of the cubes were measured at two different frequency bands,

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namely, S-band (2.6–3.95 GHz) and X-band (8.2–12.4 GHz), using open-ended rectangular waveguide probes in conjunction with an HP8510C vector network analyzer [10]. This procedure was repeated for three such soaking and drying cycles. In addition to the reflection properties, the mass of the cubes was also measured on a daily basis. The analysis of the measured results is performed for two specific frequencies of 3 GHz (S-band) and 10 GHz (X-band), representing each frequency band.

III. Experimental Results

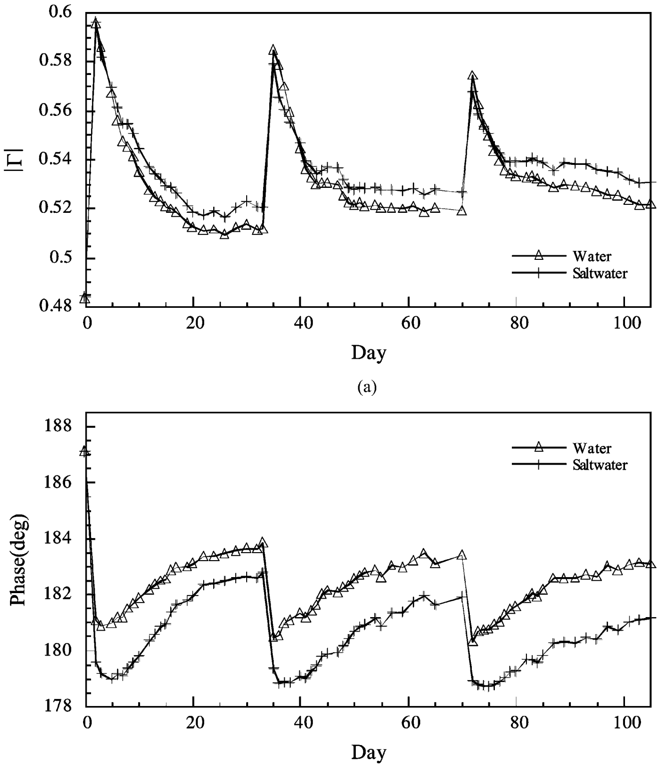
The calibrated reflection coefficient of the cube is a complex parameter consisting of a magnitude and a phase for a specific frequency. A detailed discussion of the experimental results is given in [10] and will not be repeated here. However, the important features of the experimental results as it pertains to the development of the model are mentioned here. Fig. 1(a) and (b) shows the daily measured magnitude ($|\Gamma|$) and phase of reflection coefficient of the cubes for three soaking cycles at 3 GHz. The results indicate that there is: 1) a gradual decrease in $|\Gamma|$ and 2) a progressive increase in the measured phase of reflection coefficient as a function of increasing days, both primarily indicating the evaporation of water from the cube. However, their overall behavior is indicative of more complex phenomena involving the temporal distribution of moisture and its movement within the cubes [10], [11]. The variations in the reflection properties as a function of days are as a result of specific phenomena that occur within these cubes. To obtain a better understanding of these phenomena, a modeling process was initiated [11]–[13]. Such a model would then describe the state of the cubes with respect to the temporal distribution of the various inclusions such as water, saltwater, pore volume, etc., and various transport phenomena such as capillary draw, diffusion, etc.

IV. Modeling Considerations

The reflection properties of the cube for a given frequency are dependent on its effective complex dielectric properties. "Effective" refers to the fact that the dielectric properties of the cube vary from its surface toward its core during the drying cycle, since the water/saltwater distribution within it continually changes. Thus, the primary requirement for the development of the model is the conceptualization of the various phenomena that might be occurring within the cube and, more importantly, how they influence the dielectric properties as a function of days and depth into the cube.

A. Water-Soaked Cube

When soaked, water fills some of the preexisting pores/cracks in the mortar cube. Thus, soaked mortar comprises a base or host material (i.e., mixture of hardened cement paste and sand) and air and water as its two primary inclusions. Therefore, the effective complex dielectric properties of mortar are dependent upon the volume fraction and the individual dielectric properties of the host and its inclusions and their distribution throughout the cube. When the soaked cube is analyzed or modeled as a collection of discrete layers, it is quite obvious that each of the layers would have varying water content that changes during each day of the cycle [11], [12]. Consequently, the amount of water that evaporates from each layer is dependent on its relative distance from the surface of the cube. Additionally, due to various other phenomena (such as absorption, diffusion, permeation, wicking, and capillary draw) moisture also moves between the layers. Hence, to be able to predict the temporal water content in each layer it is necessary to model not only the amount of water that is lost by each of the layers due to evaporation but also the amount of water that *moves* among the layers [11], [12].



(a)

(b)

Fig. 1. (a) Magnitude and (b) phase of reflection coefficient at 3 GHz for three cycles.

B. Saltwater-Soaked Cube

The extensive modeling of the water-soaked cube was of great significance in that it provided an insight into the various phenomena that might be occurring within the cube and, more importantly, how they can be represented in terms of electromagnetic quantities. However, once the modeling of the saltwater-soaked cube was initiated, it became evident that these phenomena alone would prove insufficient for the accurate simulation of the reflection properties of the saltwater-soaked cube. The model thus had to be modified to account for the additional phenomena that might be occurring due to the presence of salt [11], [13].

Once soaked, the saltwater penetrates into the cube filling existing cracks and/or pores. As water evaporates from the cube and the pore solution reaches its saturation concentration in localized regions within the cube, salt crystals precipitate out in the preexisting pores and cracks [13]. In addition, some of the intruding chloride ions interact with calcium aluminate phases present in the cement paste, thus forming bound salt. Thus, the soaked mortar cube can be represented as a multiphase dielectric mixture, where the host material comprises hardened cement paste, and sand while pore solution, salt crystals, bound salt, and air (pores and cracks) constitute the inclusions. Once removed from the bath and exposed to the ambient conditions, the saltwater in the cube begins to evaporate from its near surface regions while some of the saltwater is drawn toward the core through the process of capillary draw, as was the case for the water-soaked cube. With drying, dissolved salts begin to precipitate as salt crystals, filling existing pores in the cube (unlike as in the water-soaked cube). Therefore, the various inclusions present in the cube temporally vary in distribution as well as in volume content in a given cycle.

V. MODELING APPROACH

A detailed discussion of the modeling process is given in [11]–[13], where it has been shown that the water content distribution within the cubes can be represented with a Rayleigh-like function. Equation (1) shows the general form of the distribution function employed in the models

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

where t is the distance from the surface of the cube and assumes values ranging from 0 (surface of the cube) to 100 mm (center of cube). k_1, k_2, k_3 are empirical parameters and k_4 is the amplitude of the distribution function for each day. The empirical parameters k_1, k_2, k_3 were obtained from a rigorous trial and error method by matching the simulation results with the measured reflection coefficient results. The values of these parameters change as a function of days, as a consequence of which the characteristics of the distribution curves such as their shape and position of the peak water/saltwater content vary as a function of days and depth into the cube.

To model the reflection properties of the cubes, a multilayered formulation of a layered structure was considered [14]. The dielectric properties of each layer needed as input to the model are directly related to the dielectric properties and volume content of the host (i.e., mortar) and the various inclusions in each layer. Therefore, the results will be directly dependent on the volume content of the inclusions in each layer resulting in the sought-for water/saltwater content distribution within the cube. The dielectric properties of each layer can be calculated using a number of dielectric mixing models [15], [16]. Dielectric mixing models give the effective dielectric properties of a mixture composed of a host material (i.e., mixture of hardened cement paste and sand) and several constituents (i.e., air, water, saltwater, crystalline salt, etc.) as a function of the temporally varying dielectric properties and volumetric content of the host and the inclusions.

The modeling process for the water-soaked cube revealed certain important aspects regarding the temporal water distribution within the cube. It was determined that to properly simulate the shape of the phase of reflection coefficient during the first few days of drying (i.e., where it exhibits a flattened shape), the distance at which the peak of water distribution functions occurred could not remain fixed, and varied as a function of days, indicating the movement of water between the layers. To simulate this effect the values of the empirical parameters k_1, k_2, k_3, and k_4 also changed as a function of days [12].

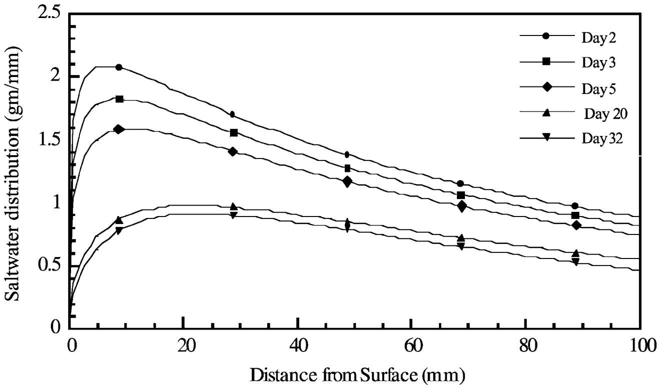


Fig. 2. Saltwater distribution—cycle 1.

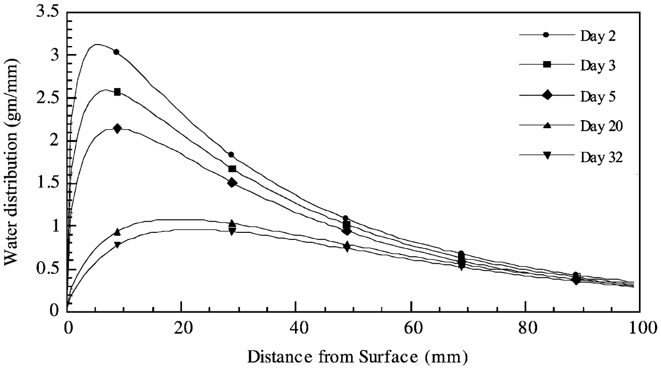


Fig. 3. Water distribution—cycle 1.

The model that was developed for the water-soaked cube was then modified to simulate the reflection properties of the saltwater-soaked cube allowing for the additional influences caused by the presence of salt [11], [13]. One of the major modifications to the model was the replacement of water (in the case of the water-soaked cube) with crystalline salt, bound salt, and saltwater (in the case of the saltwater-soaked cube). Additionally, as the water evaporates from the saltwater-soaked cube, the salinity of the remaining pore solution increases. Once these issues were accounted for and appropriately represented in the model, the multilayered formulation was once again invoked to simulate the reflection properties of the saltwater-soaked cube. The outcome of the modeling process was then the sought-for water or saltwater distribution within the cubes and their temporal variations.

VI. MODELING RESULTS

The outcome of the semiempirical model gives the temporal water and saltwater distributions within the respective cubes. Figs. 2 and 3 show the saltwater and water distribution curves, respectively, as a function of distance into the cube for several days of the first cycle. The results indicate certain contrasting features between the water and saltwater distributions as well as the manner in which they vary as a function of days. A preliminary comparison of the distribution curves—in particular, the tail-end of the curves—clearly shows that while in the case of water the tail-end remains more or less fixed, in the case of saltwater there is a gradual decrease as a function of days. This is primarily an indication of the different manners by which the water/saltwater is drawn from the cubes for the two cases.

The water/saltwater present in the cubes is primarily subject to two concurrent processes: evaporation and diffusion. The phenomena of diffusion are governed by the difference in concentration of water/saltwater between the layers, the result of which is the movement of water/saltwater from regions of higher concentration to those of lower concentration. Based on the distributions shown in Figs. 2 and 3, it is quite obvious that the regions of lower concentration exist toward the core while the regions of higher concentration exist toward the surface. Thus, it can be hypothesized that the water/saltwater moves toward the core due to diffusion. This movement, however, is counteracted by the movement of water/saltwater toward the surface due to the evaporation process. A comparison of the distribution curves for the water and saltwater cubes in conjunction with the hypothesis related to diffusion and evaporation allows us to arrive at the following inferences.

In the case of the water-soaked cube, the evaporation process is the dominating factor. This effect, however, diminishes and is increasingly counteracted by the diffusion process as we move from the surface toward the core. This causes the tail-end of the distribution curves to remain at a fairly constant water content level throughout the cycle. In the case of the saltwater-soaked cube, although the evaporation process is still the dominating factor, its effect is not totally counteracted by the diffusion process as we move from the surface toward the core. This implies that there is still a net flow of saltwater from the core toward the surface after which it evaporates from the cube. Due to this net movement, there is a consistent reduction in the saltwater content level in the tail-end of the curves as a function of days.

During the period that the cubes are immersed in their respective baths, the permeation of water/saltwater is primarily due to capillary draw. To obtain a clear understanding of this phenomenon, it is necessary to compare the water and saltwater distributions immediately after extraction of the cubes from their respective baths. Throughout the course of this investigation, the first measurement corresponded to 24 hours after removing the cubes from the baths, referred to as "day 2" in the figures. This was done to allow the excess free water/saltwater near the surface of the cubes to evaporate (drip out). Thus, the model results do not include the distribution that existed within the cubes immediately after extraction. However, it is believed that during this initial period of time, the mass of water/saltwater that evaporates is primarily from the near-surface regions. This implies that the distribution of water/saltwater beyond the first few millimeters, for day 2, would still render useful information regarding the phenomenon of capillary draw. A comparison of the two figures (for day 2) indicates that the saltwater content decreases less rapidly as a function of distance into the cube as compared to the water content. This aspect is also evident from the latter half of the distribution curves, which are higher for saltwater. Additionally, the peak of the distribution curve is noticeably higher for the water-soaked cube. It should be noted here that both cubes absorbed approximately the same amount of water and saltwater respectively during the soaking period [10]. From these comparisons it can be inferred that for a similar uptake of water and saltwater there is a marked difference in the distribution within the cube. It is believed that these differences in the distribution arise from the manner by which water and saltwater are drawn into mortar (absorption process).

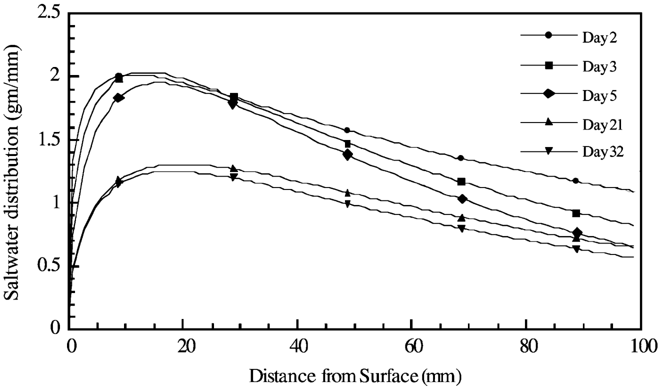


Fig. 4. Saltwater distribution—cycle 2.

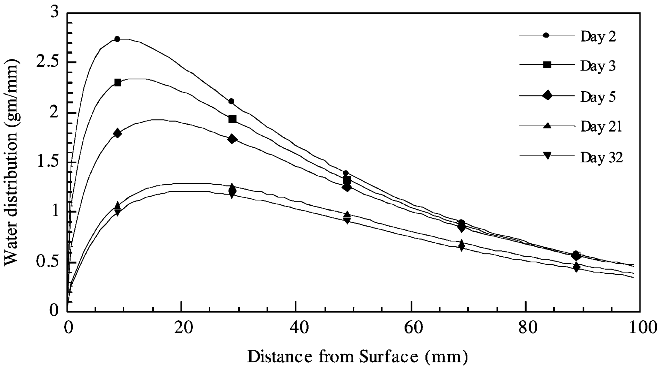


Fig. 5. Water distribution—cycle 2.

Figs. 4 and 5 show the saltwater and water distribution curves for cycle 2. A comparison of cycles 1 and 2 indicates that for the first day (day 2) of cycle 2, the peak of the water/saltwater content is lower than that of cycle 1 for both the water and saltwater cases with the difference being slightly higher in the case of water. This is primarily due to the presence of residual water/saltwater from the last days of cycle 1, which hinders the permeation of additional water/saltwater when the cubes are once again soaked [10], [11]. The distribution curves for cycle 2 indicate that they are mostly consistent with those of cycle 1 results, with a notable exception. In the case of water, the peak of the distribution curves decreases rapidly during the first few days of the cycle, while the tail-end remains fairly constant. This once again shows that the effect of evaporation is increasingly counteracted by the diffusion process, as was the case in cycle 1. The notable exception, however, occurs in the case of saltwater. During the first few days of the cycle, the change in the saltwater content in the near-surface layers is significantly less compared to that of cycle 1. There is actually a slight increase in the peak saltwater content from day 2 to day 3. However, to compensate for the mass of water that evaporates from the cube, there is a significant decrease in the saltwater content toward the tail-end of the curve. This essentially means that although evaporation is once again the dominating factor, its effect does not

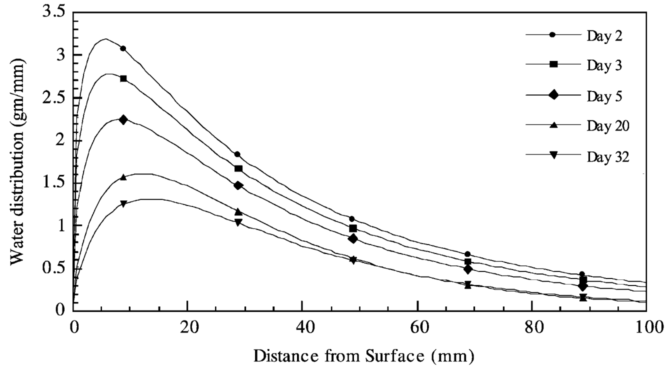


Fig. 6. Modified water distribution—cycle 1.

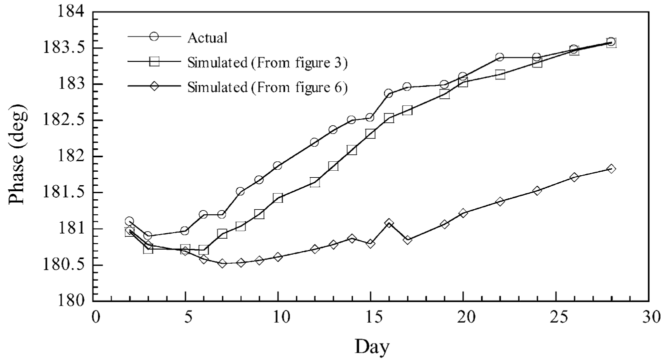


Fig. 7. Phase of reflection coefficient at 3 GHz for two different water distributions.

significantly diminish as a function of thickness into the cube. This implies that the net flow of saltwater from the core toward the surface is significantly greater than in cycle 1. One of the possible reasons for this increase in the net flow from cycle 1 to cycle 2 may be the hygroscopic properties of salt, which cause it to hold onto the water for a longer period of time. This property of salt becomes more pronounced in cycle 2, since more salt is now present in the cubes (especially toward the surface) as a result of two factors: a) the residual salt left behind in the cube from cycle 1 and b) the additional saltwater that has permeated into the cube during the second cycle. Similar traits in the distribution curves were also observed for cycle 3 in the case of both water and saltwater cubes.

The comparison of the results for the water-soaked and the saltwater-soaked cubes, based on the their distributions, clearly shows differences in the manner by which they vary *temporally*. However, to confirm that these differences do actually exist, and more importantly that they are as a result of the presence of salt, it becomes imperative to verify the uniqueness of the distribution curves. Ideally, the uniqueness of these curves can be verified by showing that no other set of distribution curves is capable of simulating the reflection properties for either cube at two different frequency bands (S-band and X-band) accurately. However, the same can also be achieved by showing that the reflection properties of the water-soaked cube cannot be modeled accurately, if the water distribution curves varied in a manner similar to that of the saltwater-soaked cube and vice versa. Fig. 6 shows a modified set of water distribution curves for cycle 1, which follow the behavior of saltwater curves. Fig. 7 shows the phase of reflection coefficient at 3 GHz simulated using the distribution curves in Figs. 3 and 6. The results clearly show a mismatch between the actual and simulated phase of reflection for the case with the distribution curves from Fig. 6. The inability of the new set of distribution curves (Fig. 6) to accurately simulate the reflection properties of the water-soaked cube clearly confirms that the phenomenon of mass transport is indeed different for the water and saltwater cubes, as predicted and expected. Additionally, it can then be concluded that this difference is as a result of the variation in the diffusion properties between water and saltwater.

VII. CONCLUSION

The temporal moisture distribution within a water-soaked and saltwater-soaked cube was obtained using a semiempirical electromagnetic model by matching the measured and simulated reflection property results. The simulated reflection properties are obtained from a multilayered formulation of a layered structure based on the water and saltwater distribution curves that were discussed. The results of the investigation have shown that there was good agreement between the measured and simulated reflection properties [11]–[13]. The results also indicate that although there is similarity in the temporal trends of the reflection properties of the water and saltwater cubes, their dissimilarity in value, in addition to being caused by variations in the dielectric properties of water and saltwater, was also as a result of variation in the mass transport phenomena within each respective cube.

The analysis of the water and saltwater distributions for the first two cycles indicates that there are variations in the two primary processes that concurrently occur within the cubes, namely, evaporation and diffusion, between the water and saltwater cubes. Additionally in the case of the saltwater-soaked cube, it was observed that there was a variation from cycle 1 to cycle 2. It is believed that this variation is due to the hygroscopic properties of salt, which become more pronounced for increasing number of cycles. To confirm the hypothesis that the phenomenon of mass transport varies for the water and saltwater cases, a successful uniqueness test was carried out. Based on the results of this investigation, it can be therefore concluded that although the reflection properties of the water- and saltwater-soaked cubes exhibit similar characteristics, a) there is a notable difference in the way water/saltwater is absorbed by the two cubes, i.e., capillary draw, and b) there is a variation in the way water/saltwater is drawn out of the cubes, i.e., diffusion phenomenon.

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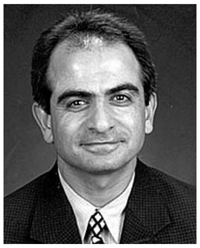
Since 2000 he has been with the Applied Microwave Nondestructive Testing Laboratory as a Graduate Research Assistant. His current research involves the evaluation of moisture and chloride ingress in cement-based material based on microwave nondestructive techniques.



Reza Zoughi (S'85–M'86–SM'93) received the B.S.E.E., M.S.E.E., and Ph.D. degrees in electrical engineering (radar remote sensing, radar systems, and microwaves) from the University of Kansas, Lawrence.

He was with the Radar Systems and Remote Sensing Laboratory (RSL) at the University of Kansas from 1981 to 1987. Currently he is the Schlumberger Distinguished Professor of Electrical and Computer Engineering at the University of Missouri-Rolla (UMR). Prior to joining UMR in January 2001 and since 1987, he was with the Electrical and Computer Engineering Department at Colorado State University (CSU), where he was a Professor and established the Applied Microwave Nondestructive Testing Laboratory. His current areas of research include developing new nondestructive techniques for microwave and millimeter wave inspection and testing of materials (NDT), developing new electromagnetic probes to measure characteristic properties of material at microwave frequencies, and developing embedded modulated scattering techniques for NDT purposes, in particular for complex composite structures. He was the Business Challenge Endowed Professor of Electrical and Computer Engineering from 1995 to 1997 while at CSU. He has more than 300 journal publications, conference proceedings and presentations, technical reports, and overview articles. He is author of *Microwave Nondestructive Testing and Evaluation Principles* (Norwood, MA: Kluwer Academic, 2000) and coauthor (with A. Bahr and N. Qaddoumi) of a chapter on "Microwave Techniques" in *Nondestructive Evaluation: Theory, Techniques, and Applications* (New York: Marcel and Dekker, 2002). He has received seven patents, all in the field of microwave nondestructive testing and evaluation. He has given numerous invited talks on the subject of microwave nondestructive testing and evaluation.

Dr. Zoughi is a member of Sigma Xi, Eta Kappa Nu, and the American Society for Nondestructive Testing (ASNT). In the past three years at UMR he has received two Outstanding Teaching Commendations and an Outstanding Teaching Award (2002–2003 academic year). He was voted the most outstanding teaching faculty seven times by the junior and senior students at the Electrical and Computer Engineering Department at CSU. He received the College of Engineering Abell Faculty Teaching Award in 1995. He is the 1996 recipient of the Colorado State Board of Agriculture Excellence in Undergraduate Teaching Award (only one faculty recognized for this award at each of the three CSU system campuses). He was recognized as an Honored Researcher for seven years by the Colorado State University Research Foundation. He is an Associate Technical Editor for the IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT and *Materials Evaluation*. He was the Guest Associate Editor for the Special Microwave NDE Issue of *Research in Nondestructive Evaluation* in 1995. He was Co-Guest Editor for the Special Issue of *Subsurface Sensing Technologies and Applications: Advances and Applications in Microwave and Millimeter Wave Nondestructive Evaluation*. He was the Research Symposium Cochair for the ASNT Spring Conference and 11th Annual Research Symposium in March 2002 in Portland, OR. He was Technical Chair for the IEEE Instrumentation and Measurement Technology Conference (IMTC2003) in May 2003 in Vail, CO. He is the Guest Editor for the IMTC2003 special issue of the IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT.