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Comparison of Water and Saltwater Movement in Mortar Based on a Semi-Empirical 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 importance to be able to non-destructively detect and evaluate the free chloride content in concrete. To that 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. A semi-empirical electromagnetic model was then 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, the distribution curves also depict the manner in which the water and saltwater contents vary within the cubes from day to day. 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 mechanism of mass transport within the cubes.

I. INTRODUCTION

Evaluation of water and saltwater distribution and its temporal movement in cement-based materials is important for assessing cement hydration, curing, and most importantly, long-term performance. Near-field microwave nondestructive evaluation methods have proven effective for evaluation of cement-based materials for their various mixture properties including the detection of salt added to the mixing water and chloride ions entering these materials through exposure to saltwater solutions [1-2]. Electromagnetic modeling of the interaction of microwave signals with moist cement-based materials can provide the necessary insight to evaluate water and saltwater content distribution and 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. A semi-empirical electromagnetic model, based on modeling the cube as a layered structure, was then developed to simulate the measured reflection properties. The most important outcome of the model is the temporal behavior of water and saltwater content distributions and hence their movement in the mortar cubes. This paper presents a comparison between the temporal water and saltwater distributions in the mortar cubes. The primary issue of interest addressed here is the variation in the water and

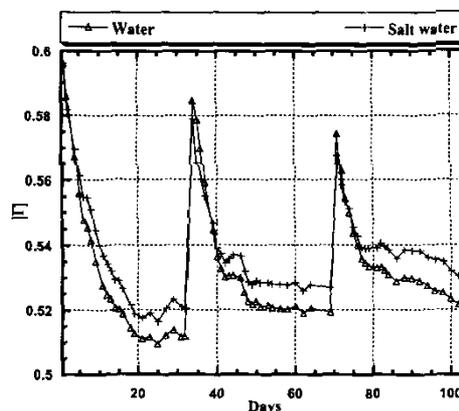
saltwater distributions in a soaking cycle as well as how they change between soaking cycles.

II. MEASUREMENT APPROACH

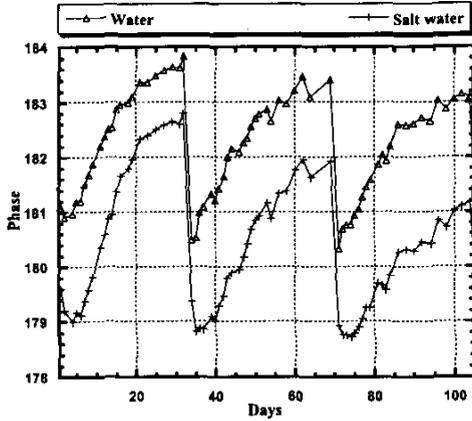
Two 8"x 8" x 8" mortar cubes having water-to-cement ratio (*w/c*) of 0.50 and sand-to-cement ratio (*s/c*) of 2.5 were submerged in (a) a distilled water bath and (b) a saltwater bath having a salinity of 2.8 % for 24 hours during each soaking cycle. The cubes were subsequently removed from the baths and left in ambient conditions for 24 hours to allow the 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, namely S-band and X-band using open-ended rectangular waveguide probes in conjunction with an HP8510C vector network analyzer. This procedure was repeated for three such soaking and drying cycles. In addition to the reflection properties, the mass of the cubes were also measured on a daily basis. The analysis of the measured results are performed for two specific frequencies of 3 GHz (S-band) and 10 GHz (X-band), representing each frequency band.

III. EXPERIMENTAL RESULTS

A detailed discussion of the experimental results is given in reference [3]. Figures 1a-b show the daily measured



(a)



(b)

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

magnitude ($|\Gamma|$) and phase of reflection coefficient of the cubes for three soaking cycles at 3 GHz. The results indicate that there is (a) a gradual reduction in $|\Gamma|$ and (b) a progressive increase in the measured phase of reflection coefficient as a function of increasing days, primarily indicating the evaporation of water from the cube. However, their overall behavior is indicative of a more complex phenomenon involving the temporal distribution of moisture and its movement within the cube [4-5].

IV. MODELING APPROACH AND CONSIDERATIONS

The variations in the reflection properties as a function of days are as a result of certain phenomena (in addition to evaporation) that occur within these cubes. To obtain a better understanding of these phenomena, a modeling process was initiated [4]. 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, etc.

A detailed discussion of the modeling process is given in reference [4-6], 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 distribution function employed in the model.

$$WD(t) = k_4 \left[\frac{t}{k_1} \right]^{k_2} e^{-\left[\frac{t}{k_3} \right]^{k_2}} \quad (\text{g/ml}) \quad (1)$$

where t is the thickness which varies from the surface of the cube to its center. 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 change as a function of days and were obtained from a rigorous trial and error method by matching the simulation with the measured reflection

coefficient results. The values of the parameters change as a function of days. Consequently, the characteristics of the distribution curves such as its shape, position of the peak water content vary as a function of days. To model the reflection properties of the cubes, a multi-layered formulation of a layered structure was considered [7]. The model that was developed for the water-soaked cube was then modified to simulate the reflection properties of the saltwater-soaked cube. One of the major modifications to the model was the replacement of water (in the case of the water-soaked cube) with crystalline 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 resolved and suitably represented in the model, the multi-layered formulation was once again invoked to simulate the reflection properties of the saltwater-soaked cube. The outcome of the modeling process would then be the sought-for water or saltwater content distribution within the cubes and their temporal variations.

V. MODELING RESULTS

The outcome of the semi-empirical model describes the temporal water and saltwater distributions within the respective cubes. Figures 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, especially the tail-end of the curves clearly show 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 that the phenomena of mass transport, or in simple terms, the manner in which the water/saltwater is drawn from the cubes is different for the two cases. The water/saltwater present in the cubes are subject to two concurrent processes, namely, evaporation and diffusion. The phenomena of diffusion is 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 Figures 2 and 3, it is quite obvious that the regions of lower concentration exists towards the core while the regions of higher concentration exists towards the surface. Thus, it can be hypothesized that the water/saltwater moves towards the core due to diffusion. This movement, however, is counteracted by the movement of water/saltwater towards 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. It's effect

however, diminishes and is increasingly counteracted by the diffusion process as we move from the surface towards the core. This theory explains for the tail-end of the distribution curves remaining 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, it's effect is not totally counteracted by the diffusion process as we move from the surface towards the core. This implies that there is still a net flow of saltwater from the core towards the surface after which it evaporates from the cube. Due to this net movement, there is a consistent reduction in the saltwater content level for the tail-end of the curves as a function of days.

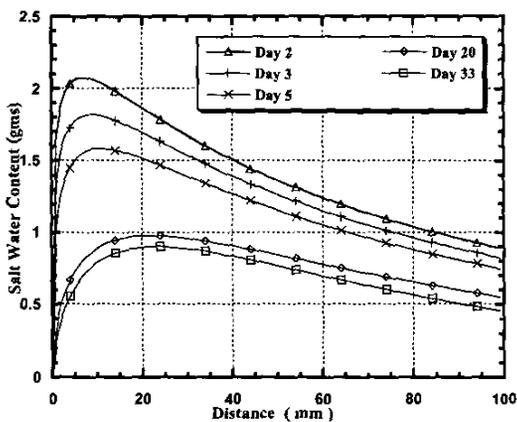


Fig 2. Saltwater distribution - cycle 1.

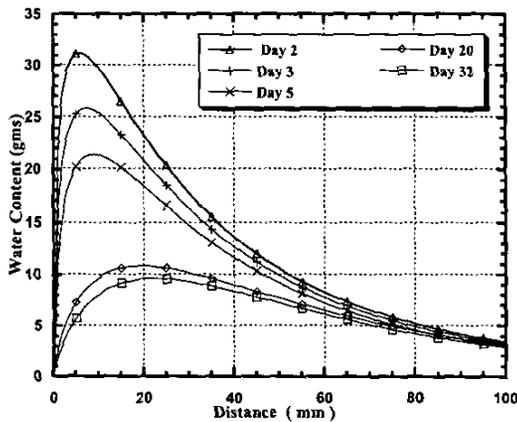


Fig 3. water distribution - cycle 1.

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 so as to allow the 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 distribution within the cube is more uniform as compared to that of water. 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 the cubes absorbed approximately the same amount of water and saltwater respectively during the soaking period [3]. From these comparisons it can be inferred that for the same 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 in which water and saltwater are drawn into mortar (absorption process).

Figures 4 and 5 show the saltwater and water distribution curves for cycle 2. A comparison of cycles 1 and 2 indicate 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 day of cycle 1, which hinders the permeation of additional water/saltwater when the cubes are once again soaked [3-4]. The distribution curves for cycle 2 indicate that they are mostly consistent with that 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 as compared to that of cycle 1. To the extent, that 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 towards the tail-end of the curve. This essentially means that although evaporation is once again the dominating factor, it's effect does not diminish as much, as a function of thickness into the cube. This implies that the net flow of saltwater from

the core towards 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 could be attributed to the hygroscopic properties of salt. The hygroscopic properties of salt causes it to hold on to the water for a longer period of time. This property of salt becomes more pronounced in cycle 2 due to the increasing amount of salt that is now present in the cubes (especially towards the surface) as a result of two factors, (a) The residual salt left behind in the cube from cycle 1 and (2) 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.

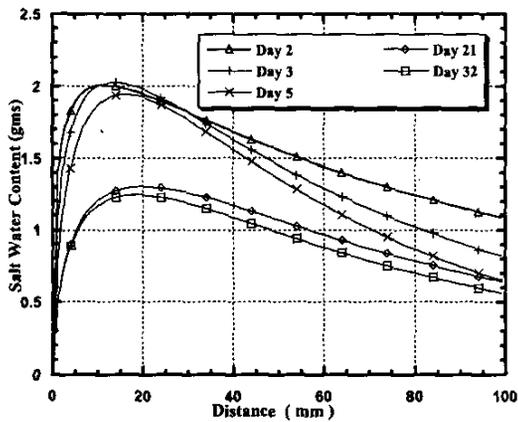


Fig 4. Saltwater distribution - cycle 2.

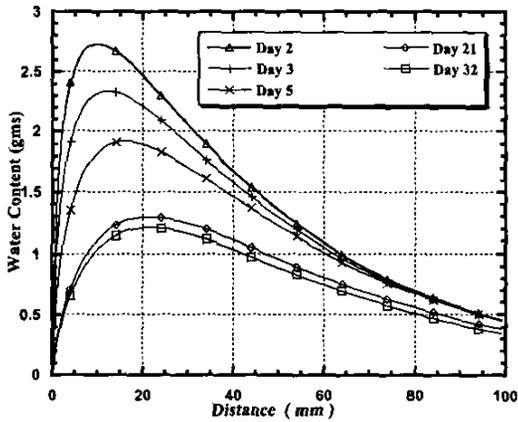


Fig 5. Water distribution - cycle 2.

The comparison of the results for the water-soaked and the saltwater-soaked cubes, based on the their distributions clearly show differences in the manner in which they vary as a function of days. However, to confirm that these differences

do actually exist, and more importantly 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 are capable of simulating the reflection properties for either cube at two different frequency bands (S 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. Figure 6 shows the new water distribution curves for cycle 1. A closer inspection of these distribution curves indicate traits similar to the saltwater distribution curves in cycle 1. Figure 7 shows the phase of reflection coefficient at 3 GHz simulated using the distribution curves in figure 3 and figure 6. The results

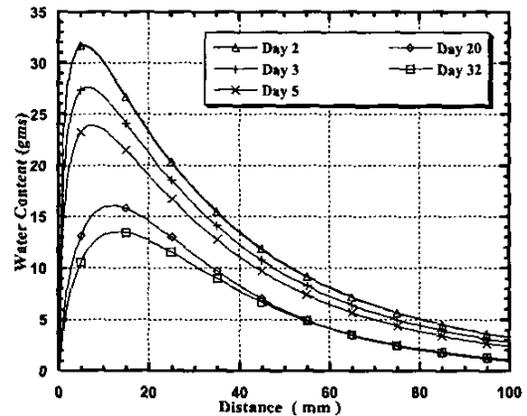


Fig 6. Modified water distribution - cycle 1.

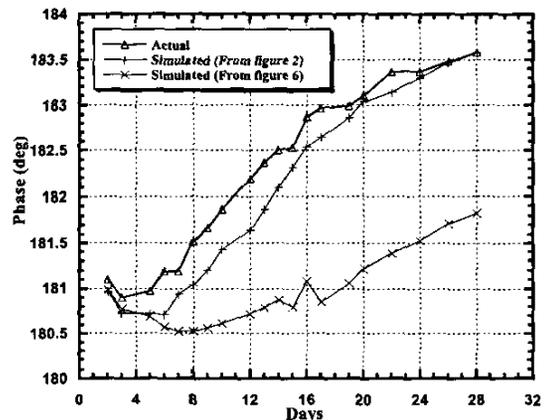


Fig 7. Phase of reflection properties.

clearly show a mismatch between the actual and simulated phase of reflection for the case with the distribution curves

from Figure 6. The inability of the new set of distribution curves (Figure 6) to accurately simulate the reflection properties clearly confirms that the phenomenon of mass transport is indeed different for the water and saltwater cubes. Additionally, it can then be concluded that this difference is as a result of the variation in the diffusion properties between water and saltwater.

VI. CONCLUSION

The distribution curves for the water and saltwater cubes were obtained from a semi-empirical electromagnetic model by matching the measured and simulated reflection property results. The simulated reflection properties are obtained from a multi-layered 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 [4-6]. The results also indicate that there is very little difference between the reflection properties of both the water and saltwater cubes as a function of days for both the cycles (see figure 1). However, the analysis of the water and saltwater distributions for the first two cycles indicate 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 also observed that there was a variation from cycle 1 to cycle 2. It is believed that this variation occurs due to the hygroscopic properties of salt which becomes more pronounced for increasing number of cycles. To confirm the theory that the phenomenon of mass transport varies for the water and saltwater cases, a uniqueness test was carried out. The results of the test were clearly in the affirmative. Based on the results of this investigation, it can therefore be concluded that although the reflection properties of the water and saltwater soaked cubes display similar characteristics, (a) there is a notable difference in the manner in which water/saltwater is absorbed by the two cubes, i.e., capillary draw, and (b) there is a variation in the manner in which water/saltwater are drawn out of the cubes, i.e., diffusion phenomenon.

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