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## Microwave Reflection Properties of Concrete Exposed Periodically to Chloride Solution of 3% Salinity and Compression Force

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**Abstract** – Microwave nondestructive evaluation (NDE) techniques applied to mortar have proven successful in the past for detecting mixture constituents, salt ingress, loading and cure state monitoring. In this paper, a similar microwave NDE technique is used to evaluate reflection properties of concrete for cyclical exposure to salt ingress and loading at S-(2.6-3.95 GHz) and X-(8.2-12.4GHz) microwave frequency bands. Four identical cubic specimens were prepared: one soaked in distilled water, one soaked in a 3%-salt solution, one soaked in a 3%-salt solution and loaded and finally one that was neither soaked nor loaded. Using both magnitude and phase of microwave reflection coefficient, it is shown that the cubes can be distinguished from one another using this technique.

### I. INTRODUCTION

Corrosion of steel compromises the strength of reinforced concrete structures, and the presence of chlorides is known to be the leading cause of such damage [1]. In recent years, microwave nondestructive testing techniques have been successfully utilized for evaluating the properties of cement-based materials [2]. It has also been shown that the same techniques can be used to detect moisture and chloride ingress inside mortar samples [3]. The present investigation focuses on concrete as opposed to mortar samples. Four concrete cubes were prepared identically and two cubes were soaked in a salt solution, one of which was loaded; one cube was soaked in distilled water; and the last cube was neither soaked nor loaded to serve as a control sample. Chloride ingress was stimulated by soaking cycles, which resembles the real environment. During the entire course of the experiment, daily microwave reflection properties were monitored at S- (2.6-3.95 GHz) and X- (8.2-12.4 GHz) microwave bands.

### II. APPROACH

Four 8"x8"x8" mortar cubes were prepared with water-to-cement ratio (*w/c*) of 0.71, sand-to-cement ratio (*s/c*) of 2.96, and coarse aggregate-to-cement ratio (*ca/c*) of 3.65 using Portland cement Type I. These mixture parameters were determined for a sample of relatively low strength, 3000 psi, and high permeability [4]. Actual strength was found to be 3300 psi from standard testing cylinders. All cubes were allowed to cure for one day in a hydration room and

subsequently stored for three months in ambient conditions. After curing, the top surface of all cubes was ground until smooth using a 6" flat rotating disk grinder to allow even distribution of the compressive load to be described later. Microwave reflection properties were measured at S- (2.6-3.95 GHz / 4 points per side) and X- (8.2-12.4 GHz / 9 points per side) microwave bands using open-ended rectangular waveguide probes in conjunction with a calibrated HP8510C vector network analyzer for four soaking cycles. Each cycle included soaking two cubes in a 3% salinity sodium chloride solution and one in distilled water for 72 hours in three individually covered containers. Each sample was placed on small spacers supporting the corners to allow unimpeded moisture ingress into all sides of the cube, excluding the top. The top one centimeter of the cube was not submerged. The fourth cube was kept in ambient conditions and never exposed to any solution or loading to serve as a reference and provide information about the influence of ambient conditions (i.e. variations of relative humidity and temperature). After soaking, the microwave reflection properties of all cubes were measured immediately and then daily for 63 days. During this time, the mass of the cubes and the ambient conditions were monitored daily as well. Remaining cycles differed from the first in that one of the cubes previously soaked in salt solution was loaded to 90,000 lbs (1400 psi) of compressive force. This was done by utilizing a 120,000 lb capacity Tinius and Olson testing machine to load the cube at a rate of 300 lb/s (136 kg/s) and unload at the same rate.

### III. RESULTS

Figure 1 shows the magnitude of reflection properties, henceforth referred to as  $|\Gamma|$ , at 3 GHz. The results indicate that there is a significant increase in  $|\Gamma|$  from day zero to day one for all the cubes. In the context of this investigation, day zero corresponds to the day prior to soaking, while day one corresponds to the measurement conducted immediately after removing the cubes from their respective baths. This increase in  $|\Gamma|$  can primarily be attributed to the presence of water-based solution, which has much higher dielectric properties than mortar [5]. This fact is also confirmed by a comparison of the wet cubes with the reference cube. Additionally,  $|\Gamma|$  for the second day after soaking is much lower than the previous day for all cycles, because much surface moisture is lost

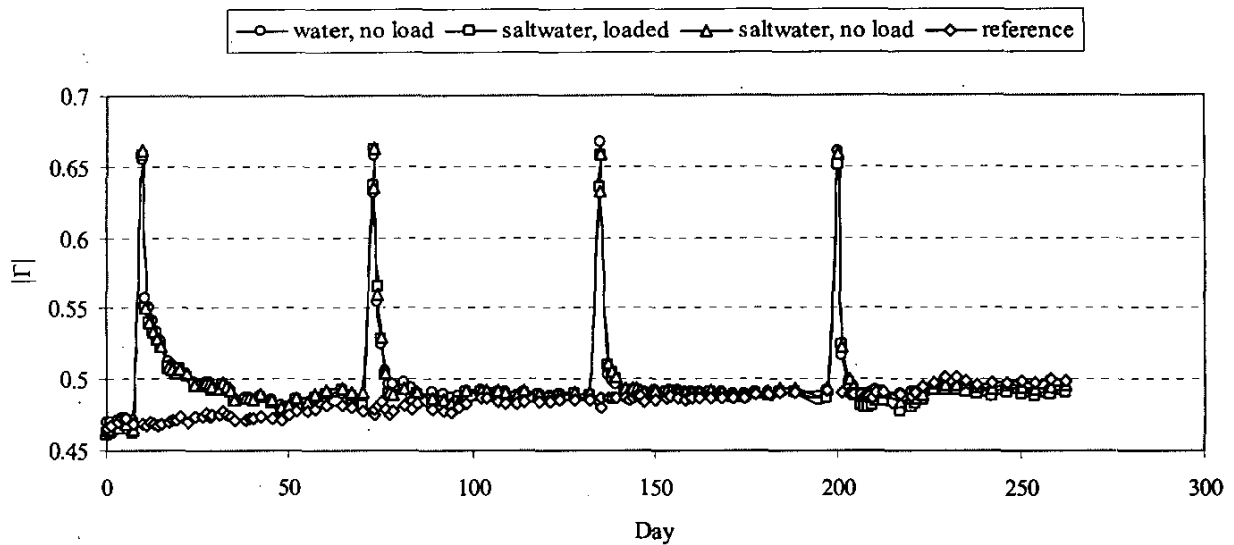


Fig. 1. Magnitude of microwave reflection coefficient,  $|\Gamma|$ , at S-band (3GHz).

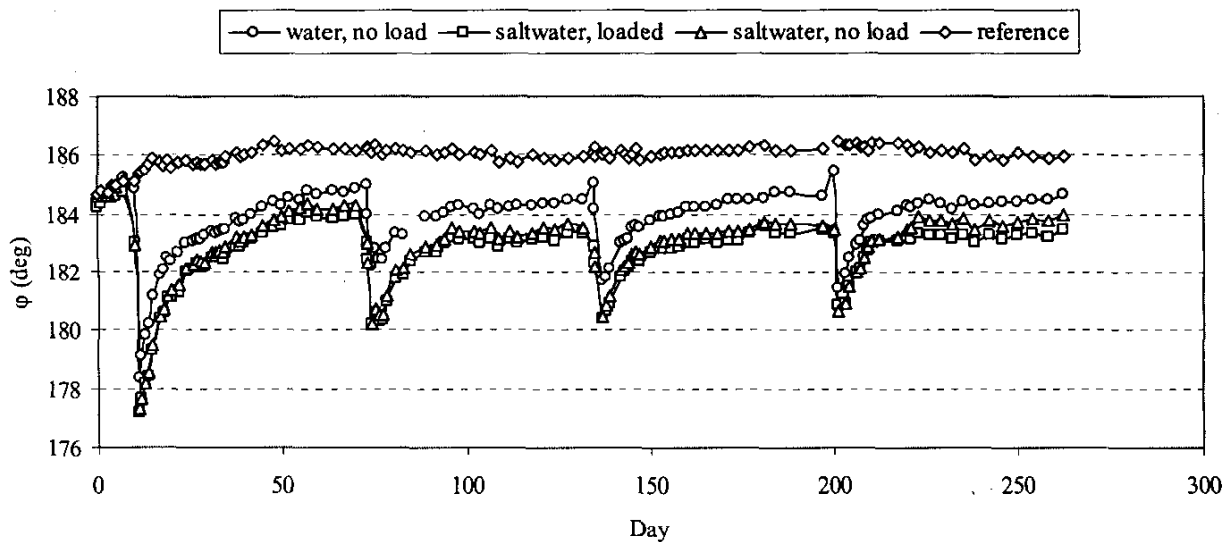


Fig. 2. Phase of microwave reflection coefficient,  $\phi$ , at S-band (3GHz).

primarily due to evaporation during the first 24 hours following soaking. This difference, however, diminishes as a function of days, primarily indicating the process of evaporation of water from these cubes. Towards the final days of each cycle, it is observed that the  $|\Gamma|$  for all the cubes converge towards the reference cube. This is an indication that much of the moisture has evaporated from the cubes, to the extent that the cubes can now be considered to be relatively dry. One may also see that the rate of decline of  $|\Gamma|$  increases as cycle number increases. This could mean that

the process of soaking flushes the pores thereby allowing the surface to dry more easily for later cycles.

Although, the magnitude of reflection properties for all the cubes display similar characteristics in both trend and value, the phase of reflection properties henceforth referred to as  $\phi$ , indicate that there is a noticeable difference between the cubes, as shown in Figure 2. It is observed that the saltwater-soaked cubes have a much lower  $\phi$  than the distilled water-soaked cube. This is because saltwater having a salinity of 3% has a much greater loss factor than distilled water [5].

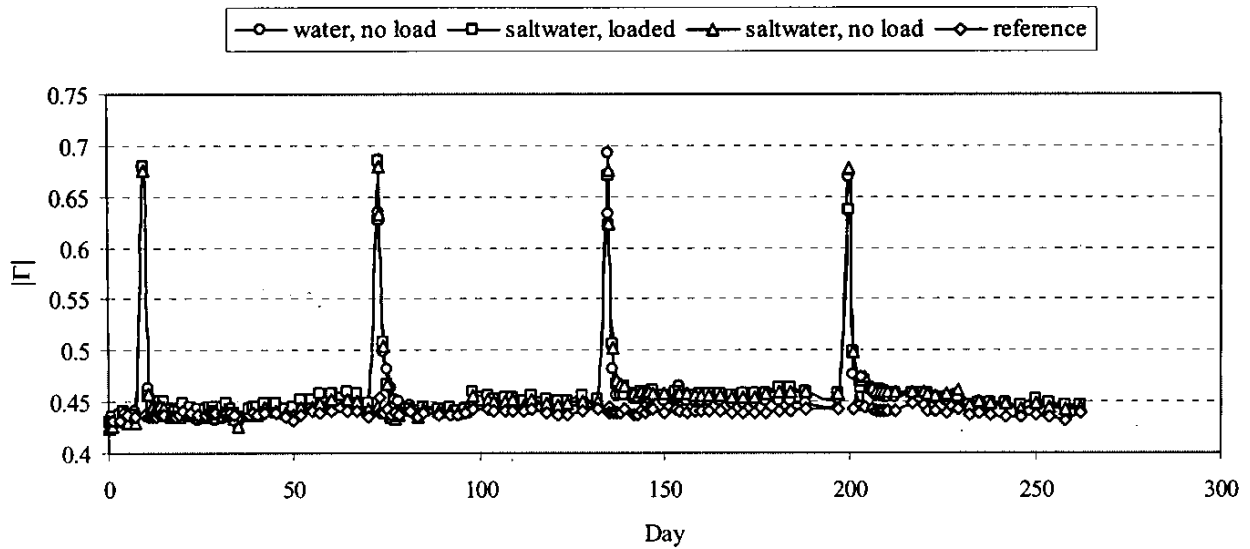


Fig. 3. Magnitude of microwave reflection coefficient,  $|\Gamma|$ , at X-band (10GHz).

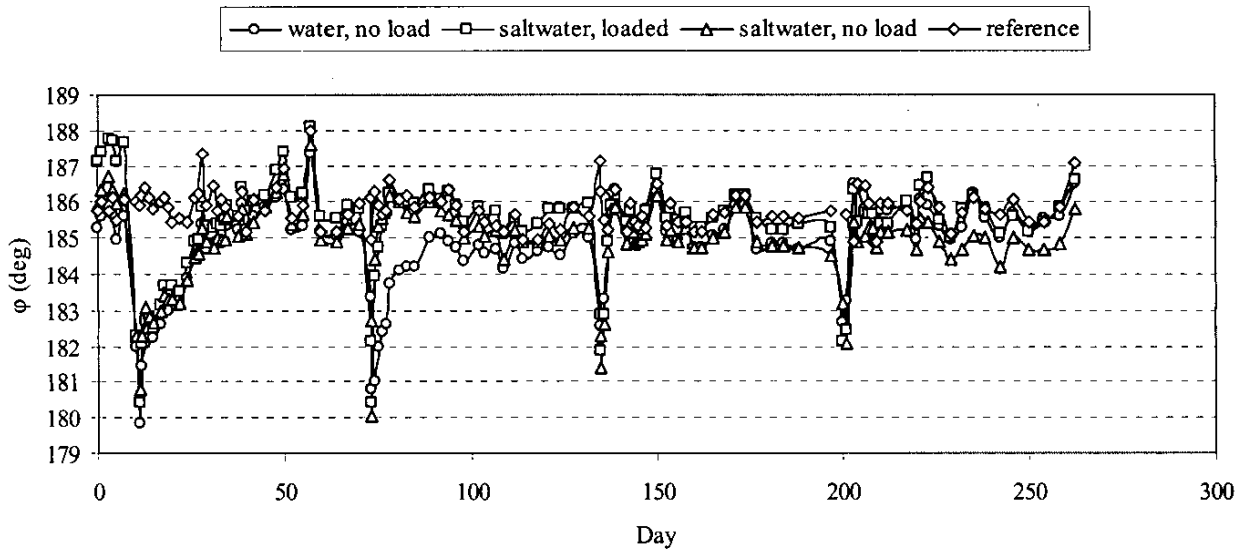


Fig. 4. Phase of microwave reflection coefficient,  $\phi$ , at X-band (10GHz).

Therefore, saltwater absorbs more microwave energy than distilled water and causes  $\phi$  to be lower. This difference in  $\phi$  may also be attributed to the hygroscopic properties of salt, which may reduce the ability of water to evaporate from the cubes. Hence, saltwater cubes will have a lower  $\phi$  as compared to the water soaked cube as the active drying cycle progresses. As the cycle nears its end, the remaining difference may be attributed to the salt left behind.

It is also important to point out that  $\phi$  dips at the beginning of each cycle and then increases for soaked samples. Since

the distilled water soaked cube also exhibits this behavior, this phenomenon cannot solely be a contribution of increasing loss factor due to increasing salinity of the pore solution during the evaporation process [5]. Instead, this trait is an indication of the time variation of moisture distribution inside the cube as well as the peak of water content within the cube [6]. As the active drying cycle progresses, it is observed for each cycle that  $\phi$  increases towards the dry reference cube, showing from a microwave standpoint that the blocks are indeed drying. It is also seen that the lowest value of  $\phi$

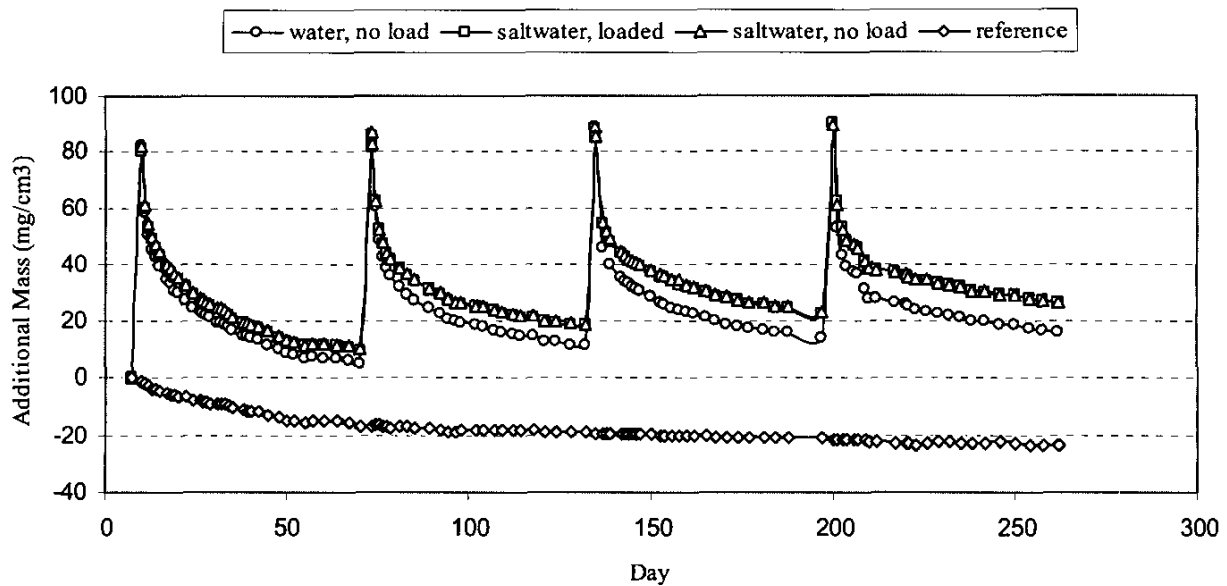


Fig. 5. Additional mass per unit volume for all cubes.

for soaked cubes in a given cycle increases as cycle number increases. This corresponds to the rapid decrease in  $|\Gamma|$  because the cubes look more like the dry reference cube earlier on in the active drying cycle.

Evidence of loading on the cubes is small and is a strong function of cycle as can be seen from Figure 2. Compressive loading produces microcracks, and it is hypothesized that these microcracks will fill with solution and allow more solution to permeate the cube. As more water is contained within the cube, the effect of saltwater on the microwave reflection properties becomes more profound, thereby making  $\phi$  lower as a function of loading. This effect can be seen in Figure 2 where the saltwater, loaded cube increasingly differs from the saltwater, no load cube.

Results at X-band are similar to S-band in that first peaks of  $|\Gamma|$  are exceptionally high followed by a period of drying i.e., Figure 3. X-band results are also particularly sensitive to near surface properties as compared to S-band, because the wavelength is smaller. Results of  $\phi$  behave similarly to S-band, but they exist over a smaller range of phase values as depicted in Figure 4. Also, the difference that exists in  $\phi$  between the saltwater-soaked cubes and the distilled water-soaked cube is not as apparent in X-band as it was in S-band. This is due to the fact that the dielectric properties of distilled water and saltwater are not as different at X-band as they are at S-band [5-6]. However, since microwave reflection properties at X-band are more sensitive to surface properties or the properties of the material near the surface, they may be used in combination with S-band reflection measurements to determine the moisture distribution inside the cube [6].

Additional mass per unit volume of the cube (Figure 5) is defined as the mass of the cube subtracted by the day zero mass and then divided by the entire volume. This information serves as a complimentary piece of data to the microwave measurements in that a one-to-one correspondence may be established between the reflection properties and the amount of solution present in the cubes. This relationship can then be used as a guiding factor for the development of a semi-empirical model that could simulate the reflection properties of the cubes. The outcome of such a model would then describe the temporal solution distribution within the cubes as a function of thickness into the cubes for each day of the cycle [6].

As seen in Figure 5, the saltwater soaked cubes lose mass slower than the cubes soaked in distilled water. This is most likely due to the fact that the salt content in the saltwater soaked cubes prevent the water from evaporating as easily as the water soaked cube, as hypothesized earlier. It is also observed that the mass of the cubes for the first and last days of the cycle progressively increase as a function of cycles. Since the cube soaked in merely distilled water also exhibits this behavior, it is obvious that there has to be a common explanation for this phenomena, the differences in the drying mechanism of water and saltwater notwithstanding. One of the possible explanations for this phenomenon could be that not all of the moisture leaves the cube by the end of the cycle, and this mass contributes to the total mass of the next soaking cycle. The gradual increase in the separation between the water and saltwater soaked cubes as a function of cycles, could be a result of the increasing amount of residual salt that is left behind in the cube as water evaporates from the

saltwater soaked cube. Therefore, additional mass provides information of average salt content as well as supporting microwave reflection measurements.

### SUMMARY

Results of daily microwave reflection measurements were presented for four concrete cubes. One was soaked in distilled water; two were soaked in a 3% salinity sodium chloride solution, one of which was loaded to 90,000 lbs; and one was kept in ambient conditions. The purpose of this investigation was to determine whether near-field microwave reflection properties are sensitive to the effects of a cyclical chloride exposure regimen combined with loading. The results at S-band (3 GHz) show a significant difference in  $\phi$  between the saltwater-soaked and distilled water soaked cubes. The results at X-band (10 GHz) are consistent with those at S-band. The analysis of the two bands in conjunction may allow for the estimation of water based solution distribution within the cube. The additional mass per unit volume also serves as complimentary data to the reflection property measurements. Based on the results of this investigation, it can however be concluded that microwave reflection properties are indeed sensitive to the effects of cyclical moisture and chloride ingress as well as compressive loading. Additionally, the results at 3 GHz are clearly able to distinguish between the water and saltwater soaked cubes. However, further study is required to relate microwave measurements to physical changes in the sample caused by chloride exposure and compressive loading.

### ACKNOWLEDGEMENT

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