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Parameters Affecting the Measurements of Embedded Electrical Sensors for Concrete Health Monitoring Applications

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Synopsis: Traditional methods of condition assessment frequently rely on manual inspections of a structure to locate signs of aging and deterioration. In comparison, the sensor-based health monitoring shows several advantages including increased accuracy and frequency of the measurements, possibility of remote sensing, and ability to determine the rate of damage and remaining life of a structure. Several sensors have been developed to monitor the durability of concrete. Among these, a series of electrical/electro-chemical sensors have been recently introduced that enable measuring the transport properties of concrete as well as monitoring the corrosion process of the reinforcing steel. In this paper, several types of such electrical sensors are introduced and the theoretical background behind each measurement is discussed. For example, it is shown that measurement of the electrical conductivity of concrete can be used to estimate the permeability, ion diffusivity, or moisture content of concrete.

Although the embedded electrical sensors provide valuable measurements enabling prediction of concrete durability, proper calibration of the measurements is essential. As an example, the electrical conductivity measurements of concrete are shown to be simultaneously influenced by four parameters: (a) concrete microstructure, (b) pore fluid composition, (c) moisture content, and (d) temperature. Experimental evidence is provided suggesting that the sensor measurements must be calibrated to account for these parameters; otherwise, the results can be misleading. A combination of several sensors can provide the information needed for proper calibration of the measurements.

Keywords: corrosion; durability; electrical measurement; health monitoring; sensor

Biography:

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1.0 INTRODUCTION

Reinforced concrete structures are subjected to aging and gradual deterioration. If symptoms of durability problems are diagnosed early, preventative measures can be taken to avoid or at least slow further damage development. On the other hand, undiscovered deterioration leads to accelerated damage which often requires costly repairs and replacements.

Traditionally, to diagnose potential durability problems, routine manual inspections have been adopted for large-scale structures [1]. These manual inspections, performed every few years (e.g., every 2-5 years), often include visual inspections of the structure to locate any sign of damage development (e.g., cracking, spalling, rust stain). In addition, inspections may include some destructive or non-destructive measurements (e.g., taking cores to determine concrete strength or half-cell potential mapping to assess the risk of corrosion).

The manual inspections provide a general and qualitative assessment of the condition of a structure. However, the measurements are subjected to human error and their interpretations depend often solely on the engineering judgment of the inspector. The results provide a “snapshot in time” assessment and may not provide information on the rate of damage development or the remaining life of the structure. Also, reliable condition assessment of some hard-to-reach areas such as underwater or underground members may not be possible.

In recent years, advancement in sensing technology has enabled engineers to use embedded sensors for continuous condition assessment and health monitoring of structures [2-4]. The embedded sensors provide several advantages over the traditional inspections including the increased accuracy and frequency of the measurements as well as the possibility of remote sensing. When calibrated properly, the sensor measurements can provide a quantitative assessment of the extent and rate of damage development. Further, the results can be input into life-cycle prediction models to assess the remaining life of the structure and to examine different scenarios for repair and rehabilitations [5]. Finally, the sensing system can provide the necessary warning before acute damage development pose a safety hazard to the users.

For reinforced concrete structures, an area of particular interest has been sensors that diagnose the corrosion of reinforcing steel. Steel corrosion is known as one of the most significant sources of concrete deterioration and imposes large maintenance costs for shoreline structures, bridges, and parking garages. In recent years, several types of electrical/electro-chemical sensors have been developed to monitor the transport of moisture and ions inside concrete and to provide information on the initiation and propagation of corrosion reactions [6-14]. These sensors provide valuable measurements enabling prediction of the durability of concrete.

While the measurements from these sensors have been repeatable and reliable in controlled laboratory environments, in uncontrolled field conditions, the results can show scatter which makes their interpretation challenging [15]. This stems from the fact that the electrical properties of reinforced concrete is simultaneously influenced by several parameters including the internal temperature and moisture content of concrete [10, 15]. Internal temperature and moisture are time dependent and can vary from point to point inside concrete. As such, the sensors’ measurements should be properly calibrated to account for these influencing parameters.

In this paper, several types of electrical/electro-chemical sensors are introduced. For each sensor, a brief discussion is provided in Section 3.0 on the theoretical background behind the measurements and on the parameters that influence the results. Particularly, the measurement of electrical conductivity of concrete is discussed that is used for estimating the permeability, ion diffusivity, and moisture content of concrete. A set of experimental measurements is provided in Section 4.0 showing the dependence of electrical conductivity on four main parameters: (a) concrete microstructure, (b) composition of pore fluid, (c) moisture content, and (d) temperature. Some insight into the type of sensors that needs to be developed to improve the health monitoring of concrete is given in Section 5.0.

2.0 RESEARCH SIGNIFICANCE

Embedded electrical sensors are valuable for health monitoring of reinforced concrete structures. To obtain reliable information, it is important to understand the parameters that influence the sensor measurements and to properly calibrate the results to account for such influences. As an example, this paper discusses the measurements of electrical conductivity of concrete that are used for determining the transport properties and the moisture content of the material. It is shown that concrete conductivity is significantly influenced by four concurrently changing parameters and as such, without proper calibrations, the sensor measurements can be misleading.

3.0 ELECTRICAL SENSORS FOR HEALTH MONITORING OF REINFORCED CONCRETE

3.1 Concrete Conductivity

This sensor is composed of two embedded and non-corroding electrodes (e.g., stainless steel). The electrical resistance of concrete is measured by applying a known voltage between the electrodes and measuring the resulting current (Figure 1a) (or by applying a known current and measuring the voltage difference between electrodes). Alternatively, a four-point measurement setup can be used in which the signal electrodes used to apply the electrical current are different than the sensing electrodes used to measure the voltage difference (Figure 1b). Measurements can be performed using direct (DC) or alternating (AC) currents. AC measurements provide advantages such as faster and more stable and repeatable readings, eliminating the electrical polarization, and the use of smaller voltages that cause less perturbation to surrounding concrete.

The measured electrical resistance is converted to electrical conductivity by applying a geometry factor to normalize the influence of electrodes' and specimen's geometry:

$$\sigma = \frac{k_g}{R} \tag{1}$$

where σ (S/m) [S/in] is the conductivity of concrete, R (Ω) [Ω] is the measured resistance, and k_g (1/m) [1/in] is the geometry factor. It has been shown that the conductivity of concrete is a function of the composition, volume fraction, and tortuosity of the pore fluid and can be described as [6, 16]:

$$\sigma = \sigma_o \phi \beta \tag{2}$$

where σ_o (S/m) [S/in] is the pore fluid conductivity, ϕ (unitless) is the volume fraction of pore fluid (i.e., liquid filled porosity), and β (unitless) is the pore fluid connectivity (i.e., it accounts for the effective length and constrictions of the liquid-filled pores [17]). Since several transport properties of concrete (such as ion diffusivity and water permeability) are similarly dependent on the volume and tortuosity of the liquid-filled pores, theoretical correlations have been established between the electrical conductivity and these transport properties [18,19]:

$$D = D_o\left(\sigma/\sigma_o\right) \tag{3}$$

$$k = \frac{1}{226} d_c^{\,2}\left(\sigma/\sigma_o\right) \tag{4}$$

where D (m^2/s) [in^2/s] is the bulk ionic diffusivity of concrete (for a known penetrating substance such as NaCl), D_o (m^2/s) [in^2/s] is the diffusivity of that substance inside the pore fluid (for NaCl, $D_o = 1.484\times10^{-9}$ m^2/s [2.300×10^{-6}

$\text{in}^2\text{/s}$] can be assumed [20]), k (m^2) [in^2] is concrete's intrinsic permeability, and d_c (m) [in] is a characteristic pore size that controls permeability [19]. These expressions have been validated experimentally and good agreement between theory and experiment was observed [18, 21].

Equations (3) and (4) show that for calculation of the transport properties, in addition to concrete conductivity (σ), knowledge of the pore solution conductivity (σ_o) is required. This stems from the fact that the electrical conductivity by itself cannot quantify concrete's microstructure; rather, the ratio σ/σ_o can be related to the volume (ϕ) and connectivity (β) of the liquid-filled pores (Eq. (2)). This is further discussed in Section 4.0.

In addition, the conductivity of concrete is dependent on its moisture content and temperature [16]. This dependence has encouraged the use of insitu electrical conductivity measurements to estimate the moisture content of field concrete [7, 8, 22]. In addition to sensing applications, it is common to manually measure the electrical conductivity of concrete using a four-point setup applied to concrete's surface [23] or using the RCPT (ASTM C1202) method [24, 25]. The results of such measurements are used similarly for estimating the transport properties or the moisture content of concrete.

3.2 Half-cell Potential

The corrosion of steel inside concrete includes formation of anodic and cathodic areas at the surface of steel bars (Figure 2a). At an anodic site, iron is oxidized ($\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$) to release electrons which will be consumed by the reduction of oxygen at the cathode ($\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^-$). The electrons flow through the steel rebar from anodic to cathodic sites. Meanwhile, to maintain charge equilibrium, ions (e.g., Fe^{2+}, OH^-) move inside concrete's pore fluid and generate an electrical current flowing from anode to cathode. The current flow is the result of a potential difference (i.e., an electrical field) that forms between the anodic and cathodic areas (Figure 2b). The magnitude of the current, which is analogous to the rate of corrosion, depends on the potential gradient as well as the resistivity (i.e., inverse conductivity) of concrete [26, 27].

The magnitude of electrode potential (E) at anodic and cathodic sites (also known as the half-cell potential of anode or cathode) is dictated by the electro-chemical reactions occurring at each site. The half-cell potential of anode is lower which causes the current to flow from anode to cathode. As a result, an electrical field is formed and the potential increases gradually by moving from anode towards cathode (as shown by the equi-potential lines in Figure 2b) [28].

The magnitude of half-cell potentials can be measured with the aid of a voltmeter and a reference electrode (e.g., copper-sulfate electrode, CSE) that is embedded inside concrete or placed on its surface. It must be noted that such measurements do not reveal the true half-cell potentials of anode or cathode. Rather, they report the potential at a particular location inside concrete at which the reference electrode has been placed (for example, in Figure 2b, a potential of approximately -500mV is measured by the voltmeter) [28]. This indicates that lower potentials correspond to areas in the vicinity of a local anode. As such, by measuring the half-cell potential at several locations, possible anodic areas can be recognized. This is a common practice known as potential mapping and has been standardized by ASTM C876.

The half-cell potential mapping is a useful qualitative method to locate possible areas undergoing active corrosion. However, the measurements cannot be used quantitatively to determine the corrosion rate [29]. The readings are directly influenced by the distance between the reference electrode and a local anode as well as the electrical conductivity of concrete [28]. Other parameters influencing the measurements include the temperature and moisture content as well as the ionic composition of concrete's pore fluid [23, 27]. An additional complication exists for sensing applications which make use of embedded reference electrodes at known locations inside concrete. Unfortunately, the stability of such embedded sensors is a cause for concern as the potential of the embedded reference electrode may show considerable drift with time [23].

3.3 Chloride Concentration

The idea of using embedded reference electrodes has been expanded to measure the chloride ions concentration inside concrete's pore fluid. For this purpose, the potential of an embedded silver/silver-chloride (Ag/AgCl) electrode is measured against a separate reference electrode (e.g., MnO_2 electrode). The potential of the silver chloride electrode is a function of the activity (≈ concentration) of chloride ions in the pore fluid of surrounding concrete according to the Nernst equation [23]:

$$E = E^0 - \frac{RT}{F} \ln a_{Cl^-} \tag{5}$$

where E (mV) is the measured electrode potential, E^0 (mV) is the potential at standard conditions ($T = 298\ ^{o}K$ [536.4 ^{o}R], P = 1atm, Cl^- concentration = 1mol/lit [0.016 mol/in^3]), R (=8.314 J/mol^{o}K [40.881 lbs.in/mol^{o}R]) is the universal gas constant, T (^{o}K [^{o}R]) is the temperature, F (=96485 col/mol) is the Faraday constant, and a_{Cl-} (mol/lit [mol/in^3]) is the activity (≈ concentration) of chloride ions in the vicinity of the sensor.

Several chloride concentration sensors have been developed based on this principle [11, 22, 30]. The measurements show dependence on the moisture content and electrical conductivity of concrete and as such, proper calibration of the results is required.

3.4 Macrocell Measurements

In this setup, the galvanic corrosion current passing between an active (i.e., corroding) and a passive (i.e., non-corroding) electrode is measured (Figure 3a). Several embedded macrocell sensors have been developed including the anode ladder system developed by Raupach and Schieβl (Figure 3b) [12]. This sensor is composed of a stainless steel cathode and a ladder of black steel anodes mounted at different depths from the surface of concrete. The anodes are electrically connected to the cathode and the corrosion current flowing between each anode and the cathode is monitored. As long as the black steel bars are in the passive condition, the galvanic corrosion current is minimal. When an anode is depassivated (due to carbonation or chloride penentaration), the exchanged current increases rapidly. As a result, the sensor is capable of monitoring the depth of steel depassivation in concrete [12].

The measured corrosion current exclusively represents the rate of galvanic corrosion between active and passive electrodes. In addition, microcell (i.e., pitting) corrosion occurs at the surface of the active electrode whose magnitude cannot be monitored using the macrocell sensor. As such, the corrosion rate measured by macrocell techniques is only a fraction of the total rate of corrosion of the reinforcing steel in concrete [31]. The galvanic current is inversely proportional to the electrical resistance of concrete between the two electrodes and as such is dependent on the conductivity, moisture content, and temperature of concrete.

3.5 Corrosion Rate Measurements

Several methods are available for measuring the rate of corrosion of steel in concrete. The two most common techniques are linear polarization (LP) and electrical impedance spectroscopy (EIS). Both of these methods work based on the principle of polarizing the corroding electrode away from its equilibrium half-cell potential (E_{corr}). The measurement setup is shown if Figure 4 and includes the corroding electrode (also known as working electrode; WE), a non-corroding counter electrode (CE), and a reference electrode (RE) for potential measurements. A small polarizing potential ($\Delta E = \pm 10$mV) is applied to the working electrode and the resulting corrosion current (ΔI) flowing between the working and counter electrodes are measured. The polarization resistance ($R_p = \Delta E/\Delta I$) is calculated and used to determine the corrosion current density (i.e., corrosion rate) of the working electrode using:

$$i_{corr} = \frac{B}{R_p A} \tag{6}$$

where i_{corr} (mA/m^2 [mA/in^2]) is the corrosion rate, B (≈ 26mV) is a constant (relating to anodic and cathodic Tafel slopes [23, 26]), R_p (Ω) is the polarization resistance, and A (m^2) [in^2] is the surface area of the working electrode polarized by the experiment. The main difference between the LP and the EIS methods is the use of alternating currents in the EIS method to calculate the polarization resistance [32]. A comprehensive description of the proper measurement practices for the LP method has been published recently [33]. For both LP and EIS methods, the ohmic resistance of concrete between the working and counter electrodes must be subtracted from the polarization resistance measured before determining the actual corrosion rate.

The biggest challenge in interpreting the measurements is identifying the true surface area of the steel polarized during the experiment. As shown in Figure 4, the area of the working electrode polarized cannot be known with certainty. To improve the accuracy of the results, a guard ring is often added surrounding the counter electrode. This guard ring confines, to some extent, the exchanged current to the area directly below the counter electrode. Nevertheless, the exact surface area of the polarized steel remains uncertain and as such, the results cannot provide the actual mass loss of the corroding rebar [33].

For sensing applications, miniature versions of the measurement setup shown in Figure 4 have been developed and are available commercially [13, 14, 22, 30]. These sensors enable continuous measurement of the corrosion rate over a period of time which can be advantageous in comparison to instantaneous corrosion rate measurements performed manually [15]. Nevertheless, the embedded sensors are susceptible to problems originating from the uncertainty in the actual surface area of the polarized steel and the potential drift of the embedded reference electrodes. In addition, the measurements are influenced by the electrical conductivity of concrete as well as its moisture content and temperature [15, 33]. Proper interpretation of the measurements requires consideration of these parameters.

4.0 DISCUSSION ON THE PARAMETERS INFLUENCING THE ELECTRICAL CONDUCTIVITY OF CONCRETE

In Section 3.0, it was discussed that the measurements of embedded electrical sensors used for monitoring the durability of reinforced concrete can be influenced by parameters such as the pore fluid composition, moisture content, and temperature of concrete. In this section, we specifically focus on the interpretation of the sensors measuring the electrical conductivity of concrete. It is shown that the transport properties of concrete (e.g., its chloride diffusion coefficient) can be determined based on the measured conductivity. However, a sole measurement of concrete conductivity is not sufficient to provide a reliable estimation of the diffusion coefficient. Rather, an accurate measurement of both concrete conductivity and pore fluid conductivity is needed. It is also discussed that the conductivity measurements are influenced by the moisture content and temperature of concrete and as such, proper calibrations are required.

4.1 Materials and Experiments

To use electrical conductivity for estimation of the transport properties of concrete and to study the dependence on the composition and volume of pore fluid, a series of five mortar mixtures were prepared using a w/c of 0.40 and aggregate volume fraction of 55%. Type I portland cement was used with Blaine fineness = 360 m^2/kg [2.54×10^5 in^2/lbs] and the Bogue phase composition C_3S=60%, C_2S=12%, C_3A=12%, C_4AF=7%, and Na_2O equivalent = 0.72%. Natural river sand with fineness modulus 3.13 was used in these mixtures. The five mixtures had the same proportions, except they contained different dosages of chemical or mineral admixtures.

Table 1 summarizes the mixtures tested in this study. M1 was a plain mortar mixture. M2 was a mortar mixture in which the mixing water was replaced entirely by a 0.5 molar potassium hydroxide (KOH) solution. The alkaline solution can serve as an accelerator [34]. M3 was a mortar mixture in which 7.5% of the mixing water (by weight) was replaced with a commercially available accelerator (Pozzolith® NC 534). M4 was a mortar mixture in which 5.0% of the mixing water (by weight) was replaced with a shrinkage reducing admixture (Tetraguard® AS20). M5 was a mortar mixture in which 10.0% of the cement (by weight) was replaced with densified silica fume.

In addition, to study the dependence of electrical conductivity on the moisture content (or internal relative humidity) of concrete, two cement paste mixtures (M6 and M7) were prepared. M6 was a plain paste mixture with w/c = 0.50 and M7 was a paste mixture with w/c = 0.35 in which 5.0% of cement (by weight) was replaced with densified silica fume.

All mixtures were prepared according to the procedure of ASTM C305. Cylindrical mortar specimens (50mm [1.97in] diameter × 65mm [2.56in] height) were prepared and seal cured inside airtight plastic containers of similar size. Electrical conductivity was measured with the aid of two stainless steel electrodes (2.4mm [0.095in] diameter distanced 10mm [0.39in] center to center) embedded inside mortar at the time of casting (i.e., 2-point measurement setup). Electrical resistance of mortar between the two electrodes was measured using electrical impedance spectroscopy following the procedure described in [16]. Conductivity was obtained from the electrical resistance using Eq. (1). The measurements were performed at the laboratory temperature of 23±1ºC [73.4±1.8ºF].

Companion mortar specimens of similar geometry were prepared for pore solution extraction. After 9 days of curing, pore fluid from each specimen was extracted using a high pressure steel die according to the procedure of [35]. The extracted solutions were stored in 2.5ml [0.15in^3] plastic vials and sealed immediately to prevent carbonation. The conductivity of the extracted pore solutions was measured using a conductivity meter connected to the impedance analyzer.

To obtain the correlation between cement paste's conductivity and its moisture content, thin cylindrical specimens (12.5mm [0.50in] diameter by 100 mm [3.94in] length) were cast in acrylic molds. After 24 hours, the specimens were demolded and transferred to a moist room (23ºC [73.4ºF] and 100%RH) for 18 months of moist curing. The extended curing period was used to minimize the effect of microstructure changes on the measured conductivity of cement paste. Each paste cylinder was then cut into small prisms (8×5×2mm [0.31×0.20×0.08in]). A pair of stainless steel electrodes was attached to each prism (on the opposing 5×2mm [0.20×0.08in] faces) using conductive silver epoxy (conductivity = 3.3×10^5 S/m [8250 S/in]) manufactured by Resin Technology Group.

Complete desorption-absorption conductivity isotherms (i.e., conductivity versus relative humidity) were obtained at 23ºC [73.4ºF] and the following relative humidities: 100% (i.e., saturated surface dried), 93%, 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, and 10%. The desorption-absorption experiment was performed inside environmental chambers under controlled temperature (23ºC [73.4ºF]) and relative humidity (RH). The chambers operated under a nitrogen purge to reduce the potential for carbonation. After reaching equilibrium at a particular relative humidity, the electrical conductivity of each specimen was measured using impedance spectroscopy. Also, the moisture content was determined using mass measurements. For each cement paste, three duplicate specimens were tested. Further experimental details are provided in [16].

4.2 Results and Discussion

Figure 5 shows the electrical conductivity as a function of age for the 5 mortars studied in this work. The electrical conductivity decreases as the mortars hydrate. This observation is consistent with similar experiments performed on cement paste and concrete [6, 7]. The reduction in conductivity can be explained by equation (2) as the volume fraction (ϕ) and connectivity (β) of the pore fluid decreases significantly as hydration proceeds. As cement hydrates, water is consumed by chemical reactions, which causes the conduction paths (i.e., the liquid-filled pores) to become smaller and more tortuous. Previous work [6, 10] shows that the pore fluid conductivity (σ_o) increases with age; however, the reduction in ϕ and β outweighs the increase in σ_o and as such, the mortar conductivity (σ) decreases [36].

To estimate the transport properties, equations (3) and (4) can be employed. For this purpose, however, knowledge of the pore solution conductivity (σ_o) is also required. Unfortunately, this is often ignored by quality control engineers and even researchers. It is a public misconception that concrete conductivity can be determined, for example using the RCPT method (ASTM C1202), and used directly to evaluate concrete quality and determine its transport properties. We argue that this practice can lead to significant errors as it does not consider the important effect of pore fluid conductivity.

This can be illustrated by our measurements from the five mortar mixtures studied in this work. Figure 6 shows the mortar conductivity (σ) and the pore fluid conductivity (σ_o) measured after 9 days of hydration. If quality evaluation is based solely on the mortar conductivity, it will be concluded that mixture M5 (10%SF) has the lowest conductivity (and as such the best quality) and mixture M3 (7.5%Pozz) has the highest conductivity and therefore the lowest quality. Further, the chloride diffusivity can be calculated from equation (3) by assuming an average pore fluid conductivity (for example σ_o = 9 S/m [0.225 S/in]) for all five mixtures ($D_o = 1.484\times10^{-9}$ m^2/s [2.300×10^{-6} in^2/s] was used for diffusivity of NaCl in pore fluid [20]). These results are provided in Figure 7 (solid points) confirming that M3 and M5 has the highest and lowest diffusivity values.

However, the measured pore fluid conductivities shown in Figure 6 suggest that ignoring the value of σ_o (or assuming that σ_o is similar for all five mixtures) may not be appropriate. Although the five mortar mixtures have similar w/c and aggregate content, and have been cured similarly for 9 days, their measured pore fluid conductivities vary widely in the range 2.44 S/m [0.061 S/in] (for mixture M5) to 17.57 S/m [0.439 S/in] (for mixture M2) based on the type and dosage of the admixture used. When the actual σ_o values are used in equation (3) to calculate chloride diffusivity, the results are considerably different than the diffusivities obtained by assuming a similar σ_o value for all the mixtures. Figure 7 provides a comparison between these two sets of diffusion coefficients. When chloride diffusivity is calculated based on actual measurements of both σ and σ_o, mixture M5 (10%SF) shows to have the highest diffusivity (and therefore the lowest quality). In this case, the calculated diffusion coefficient is 14.8×10^{-12} S/m [22.94×10^{-9} S/in] which is 3.7 times larger than when an average $\sigma_o = 9$ S/m [0.225 S/in] was used for all mortar mixtures.

In summary, to evaluate the quality of concrete and especially to obtain its transport properties using electrical measurements, both concrete conductivity (σ) and pore fluid conductivity (σ_o) must be measured. The influence of pore fluid conductivity cannot be assumed to be minor. The magnitude of pore fluid conductivity can vary over a wide range based on concrete's mixture proportions (w/c and admixtures), age, and exposure history. As such, using a constant or typical value for σ_o will lead to errors in calculating concrete's transport properties.

In addition to the pore fluid conductivity, concrete conductivity can be influenced significantly by changes in its moisture content. To study the dependence of electrical conductivity on the internal humidity and moisture content, two cement paste mixtures (M6 and M7) were tested. Mature (18 months old) specimens were prepared and dried to equilibrium at known relative humidities inside environmental chambers. The equilibrium electrical conductivity and moisture content of each paste specimen were measured as a function of the relative humidity. Figure 8 shows the electrical conductivity as a function of relative humidity and moisture content. In general, conductivity is observed to decrease as the material dries to lower relative humidities. This signifies the influence of moisture on the measured conductivity value.

The σ-RH curves show significant hysteresis. This hysteresis is mainly due to the constrictions in the pore network of the cement paste and has been discussed in details in a previous paper [16]. As a result of this hysteresis, the correlation between conductivity and relative humidity is not unique and depends on the drying history of the specimen (as shown in Figure 8a for the case of RH = 50%). Consequently, insitu conductivity measurements cannot be used directly to estimate the internal relative humidity of concrete. Alternatively, a porous material with low hysteresis can be used inside concrete as an embedded sensor for insitu measurements of relative humidity [10, 16].

On the other hand, the σ-MC curves do not show hysteresis. This means that a one-to-one correlation can be established between the moisture content and the electrical conductivity of concrete irrespective of the moisture history of the material. This observation further suggests that it is the moisture content and not the relative humidity which determines the electrical conductivity of concrete exposed to drying. As such, it may be possible to use insitu electrical conductivity measurements to estimate the moisture content of concrete. Unfortunately, the σ-MC correlation is not similar for different concrete mixtures (Figure 8b) which prevents using a "master curve" to relate insitu conductivity measurements to the moisture content of concrete. Further research is needed in this area to study the dependence of the σ-MC correlation on the microstructure of concrete and the composition of pore solution.

Finally, the electrical conductivity is influenced by concrete's temperature. The temperature dependence of conductivity has been studied by several researchers [7, 37, 38] and procedures have been proposed to temperature calibrate the conductivity using an activation energy approach (i.e., using Arrhenius equation). We will not discuss the temperature effect further in this paper.

5.0 FUTURE NEEDS FOR DEVELOPMENT AND IMPLEMENTATION OF NEW SENSORS

The experimental results and discussions presented in this paper emphasize the importance of measuring concrete conductivity, pore fluid conductivity, moisture content, and temperature. These parameters have a significant influence on the measurements of embedded electrical sensors currently used for health monitoring of concrete. At present, concrete conductivity and its temperature can be measured with commercially available sensors. On the other hand, no insitu sensor is available for measuring the pore fluid conductivity or the moisture content of concrete (There are sensors that measure the relative humidity of concrete [23, 39] although their field performance is questionable. Direct measurement of concrete's moisture content in the field is not currently possible).

It was discussed earlier that measurement of pore fluid conductivity is important for accurate estimation of the transport properties of concrete. Such measurement also provides a means to monitor changes in the internal chemistry of concrete due to ion penetration, carbonation, or deteriorative reactions such as ASR. Moisture content of concrete influences its transport properties as well as the corrosion rate of reinforcing steel. In addition, moisture content is known to be significant with regards to other deterioration mechanisms such as freezing and thawing and shrinkage [40, 41].

It is important to develop and implement sensors capable of insitu monitoring of pore fluid conductivity and moisture content of concrete. Recently, a prototype sensor has been developed at Purdue University for the measurement of pore fluid conductivity [10, 36]. This sensor makes use of a porous material (e.g., natural porous stone) as an inclusion inside concrete. The sensor is initially saturated with a synthetic pore solution. After embedding inside concrete, the sensor's pore fluid gradually reaches equilibrium with the pore solution of the surrounding concrete. Since the sensor's pore structure is known, by measuring the sensor's electrical conductivity, the conductivity of pore fluid can be determined. This sensor has shown promising results in the laboratory [36] and is currently being tested at field environments.

While several sensors have been developed for insitu measurement of concrete's relative humidity [10, 23, 36, 39], none can be used directly to determine concrete's moisture content. Since electrical conductivity is directly related to concrete's moisture content, it could be possible to develop a sensor that determines the moisture content based on concrete conductivity. Further research is needed to develop the σ-MC correlations that can be applicable to field concrete.

6.0 CONCLUSIONS

Based on the observations made in this paper, the following conclusions can be drawn:

- Several types of electrical sensors are available for health monitoring of reinforced concrete structures. When calibrated properly, these sensors can measure the transport properties of concrete and monitor the initiation and propagation of steel corrosion inside concrete.
- The measurements of the electrical sensors are dependent on several factors including concrete's porous microstructure, pore fluid conductivity, concrete's moisture content, and temperature. The sensors' readings must be calibrated and normalized to account for these parameters; otherwise, the results can be misleading.
- The electrical conductivity of concrete cannot by itself represent the quality of concrete, nor can it be used to determine concrete's transport properties. The ratio of concrete to pore fluid conductivity (σ/σ_o) must be used to evaluate concrete's quality and its transport properties.
- The electrical conductivity shows a one-to-one correlation with concrete's moisture content. As such, it is potentially possible to use insitu conductivity measurements to determine the moisture content of concrete in the field.
- Correlation between the conductivity and the internal relative humidity of concrete shows significant hysteresis. As such, conductivity cannot be used directly to estimate concrete's internal humidity. Porous materials with low hysteresis may be used as embedded relative humidity sensors.
- It is important to develop and implement additional sensors to monitor concrete's pore fluid conductivity and its moisture content. These measurements provide necessary information to calibrate the readings of other electrical sensors. In addition, the proposed sensors improve health monitoring by providing information regarding changes in the internal chemistry of concrete as well as the risk of freezing and thawing and shrinkage damage.

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REFERENCES

1- Ratay, R.T., 2005, *Structural Condition Assessment*, John Wiley, Hoboken, New Jersey

2- Chang, F-K., 1999, "Structural Health Monitoring: A Summary Report", *Proceedings of the Second International Workshop on Structural Health Monitoring*, Stanford University, Stanford, California, xix-xxix

3- Adams, D.E., 2005, "Prognosis Applications and Examples", in: *Damage Prognosis for Aerospace, Civil, and Mechanical Systems*, John Wiley, West Sussex, England, 365-384

4- Balageas, D., Fritzen, C-P., and Güemes, A., 2006, *Structural Health Monitoring*, ISTE Ltd, London

5- Ferragut, T.R., Rasmussen, R., Darter, M.I., Harrington, D., and Anderson-Wilk, M., 2005, "Long-term Plan for Concrete Pavement Research and Technology – The Concrete Pavement Roadmap; Volume II: Tracks, Publication HRT-05-053", Federal Highway Administration, Washington, DC

6- Christensen, B.J., Coverdale, R.T., Olson, R.A., Ford, S.J., Garboczi, E.J., Jennings, H.M., and Mason, T.O., 1994, "Impedance Spectroscopy of Hydrating Cement-based Materials: Measurement, Interpretation, and Application", *Journal of the American Ceramic Society*, Vol. 77, No. 11, 2789-2802

7- Elkey, W., and Sellevold, E.J., 1995, "Electrical Resistivity of Concrete", Publication No. 80, Norwegian Road Research Laboratory, Oslo, Norway

8- McCarter, W.J., Ezirim, H., and Emerson, M., 1996, "Properties of Concrete in the Cover Zone: Water Penetration, Sorptivity, and Ionic Ingress", *Magazine of Concrete Research*, Vol. 48, No. 176, 149-156

9- Rajabipour, F., Weiss, W.J., Shane, J.D., Mason, T.O., and Shah, S.P., 2005, "Procedure to Interpret Electrical Conductivity Measurements in Cover Concrete during Rewetting", *ASCE Journal of Materials in Civil Engineering*, Vol. 17, No. 5, 586-594

10- Rajabipour, F., and Weiss, J., 2007, "Material Health Monitoring of Concrete by Means of Insitu Electrical Conductivity Measurements", *Cement Wapno Beton*, Vol. 2, March 2007, 76-92

11- Elsener, B., Zimmermann, L., Flückiger, D., Bürchler, D., and Böhni, H., 1997, "Chloride Penetration – Non-destructive Determination of the Free Chloride Content in Mortar and Concrete", in: *Chloride Penetration into Concrete*, L.O. Nilsson, and J.P. Ollivier (Eds.), Proceedings of the International RILEM Workshop, 17-26

12-Raupach, M., and Schieβl, P., 2001, "Macrocell Sensor Systems for Monitoring of the Corrosion Risk of the Reinforcement in Concrete Structures", *NDT&E International*, Vol. 34, 435-442

13- Broomfield, J.P., Davies, K., and Hladky, K., 2002, "The Use of Permanent Corrosion Monitoring in New and Existing Reinforced Concrete Structures", *Cement and Concrete Composites*, Vol. 24, 27-34

14- Srinivasan, R., Carkhuff, B.G., Phillips, T.E., Saffarian, H., Davis, G.D., and Raghu, S., 2005, "Miniature Wireless Full Spectrum EIS Corrosion Sensor", *2005 Tri-Service Corrosion Conference*, NACE International, National Association of Corrosion Engineers, Orlando, FL

15- Andrade, C., Alonso, C., and Sarría, J., 2002, "Corrosion Rate Evolution in Concrete Structures Exposed to the Atmosphere", *Cement and Concrete Composites*, Vol. 24, 55-64

16- Rajabipour, F., and Weiss, J., 2007, "Electrical Conductivity of Drying Cement Paste", *Materials and Structures*, Vol. 40, No.12, 1143-1160

17- Dullien, F.A.L., 1979, *Porous Media; Fluid Transport and Pore Structure*, Academic Press, New York

18- Atkinson, A., and Nickerson, A.K., 1984, "The Diffusion of Ions through Water-Saturated Cement", *Journal of Materials Science*, Vol. 19, No. 9, 3068-3078

19- Katz, A.J., and Thompson, A.H., 1986, "Quantitative Prediction of Permeability in Porous Rock", *Physical Review B*, Vol. 34, No. 11, 8179-8181