Development of Electrical Conductivity-Based Sensors for Health Monitoring of Concrete Materials

Farshad Rajabipour (Corresponding Author)
Ph.D. Candidate and Research Assistant
School of Civil Engineering
Purdue University
West Lafayette, IN 47907-1284
Email: farshad@purdue.edu
Phone: 765-494-0358
Fax: 765-496-1364

Gaurav Sant
Graduate Research Assistant
School of Civil Engineering
Purdue University
West Lafayette, IN 47907-1284
Email: gsant@purdue.edu
Phone: 765-494-0358
Fax: 765-496-1364

and

Jason Weiss
Associate Professor and Assistant Head
School of Civil Engineering
Purdue University
West Lafayette, IN 47907-1284
Email: wjweiss@purdue.edu
Phone: 765-494-2215
Fax: 765-496-1364

Number of Words: Abstract 230, Body 5667, 6 Figures (1500). Total = 7397

Submitted to the Transportation Research Board for possible presentation and publication
Date of Submission: July 31, 2006
Development of Electrical Conductivity-Based Sensors for Health Monitoring of Concrete Materials

ABSTRACT
While several structural health monitoring methods are available for assessing the applied loads, displacements, stresses, and strains in a concrete structure, very few techniques are available to enable condition assessment from a material durability viewpoint. In order to evaluate the durability performance of concrete, in situ measurements must provide information on the microstructure and internal chemistry of the material. This paper describes the development of a material sensing and health monitoring system that is designed to measure several material properties that are necessary for evaluation of the durability performance of concrete. This sensing system is composed of three electrical conductivity-based sensors and a temperature sensor. The electrical sensors include a concrete conductivity ($\sigma_t$) sensor (that monitors setting and hardening of concrete and measures microstructural and transport properties of the material), a pore solution conductivity ($\sigma_o$) sensor (that monitors changes in the internal chemistry of the system due to ion penetration or carbonation), and a conductivity-based relative humidity (RH) sensor (to monitor moisture transport and shrinkage of the material). The temperature (T) sensor enables determination of the rate of hydration and strength development of concrete while it provides information needed for temperature calibration of the electrical sensors. This paper presents an introduction to this sensing system and discusses the role of each sensor in material health monitoring of concrete. Specifically, the measurements of the concrete conductivity ($\sigma_t$) sensor are analyzed in detail.
1.0 INTRODUCTION

Civil engineers can draw on the experiences of the medical profession when it comes to evaluating the “health” of the concrete infrastructure. Traditionally, medical health monitoring is a process aimed at enhancing the physical health and increasing the life expectancy of patients. Health monitoring includes four essential components. It starts with “examination” of the patient which leads to a “diagnosis” of potential health problems. Based on this diagnosis, the doctor provides a “prescription” suggesting precautions that need to be taken to enhance the patient’s physical conditions. Finally, the doctor makes a “prognosis” of the patient’s future health.

Similarly, health monitoring of civil engineering structures include these four major components. From an engineering perspective, health monitoring has been defined as the continuous or regular monitoring of the condition of a structure or a system using insitu (and mostly non-destructive) testing (1). Based on the results of these “examinations” (e.g., the magnitude of stresses and deformations, and the residual mechanical strength), the engineer can “diagnose” the structure’s potential problems, decide whether preventative measures are required to minimize future maintenance (i.e., “prescription”), and “predict” the remaining life with the aid of life cycle prediction models (2-5).

In recent years, health monitoring has shown significant merits in civil engineering by enabling engineers to predict and prevent structural failure, thereby saving human lives and significantly reducing the structures’ cost of maintenance and repair (6). The term “Structural Health Monitoring” has been often used to refer to the assessment of the structure’s load carrying and serviceability parameters including the measurement of loads, stresses, strains, deformations, and vibrations. Meanwhile, “Material Health Monitoring” is used to refer to the assessment of parameters and material properties that primarily influence the durability aspects of concrete. Examples include the measurement of strength, elastic modulus, density, permeability, and state of steel corrosion (7,8).

In civil engineering applications, structural and material health monitoring are desired to achieve three main objectives:

- To predict and prevent failure by providing sufficient warning before a structural failure and by enabling the prediction of the remaining life of a structure (6),
- To improve service life by enabling engineers to determine if and what precautions are needed to reduce future maintenance cost (7), and
- For quality assurance and quality control purposes to evaluate the quality of construction, to assure conformance with design, and to determine pay adjustments in performance-based contracts (9).

For quality assessment and health monitoring of concrete structures, a range of non-destructive sensors (e.g., stress/strain, acoustic/ultrasonic, electrical, and temperature sensors) can be useful (7). Measurements from each of these sensors complement one another thereby providing more complete information about material development and performance. A variety of material properties and performance parameters can be measured including internal stresses and strains (10), strength (11), stiffness (12), density (12), transport properties such as permeability and ion penetrability (13,14), internal humidity (15,16), aggressive ions (such as chlorides) concentration (8), temperature and heat development (17), internal cracking (18), and corrosion potential (19).

The objective of this research is to develop new material sensing and health monitoring systems that are capable of insitu measurement of (1) material properties (e.g., permeability, diffusion coefficient) and (2) state parameters (e.g. ion concentrations, moisture content, state of...
damage such as corrosion or microcracking inside the material). The sensing system presented in this paper is novel in that it makes use of three types of electrical conductivity measurements inside the material to obtain the desired parameters.

2.0 RESEARCH SIGNIFICANCE

Electrical measurements have been shown valuable as non-invasive methods to evaluate the material properties of concrete. In addition to the measurement of microstructural parameters \((13,14)\), electrical methods have been used to monitor water and ionic penetration \((15,20-22)\) and damage development \((23,24)\) inside concrete. However, a major problem exists in using electrical measurements for monitoring the properties of concrete. The electrical properties of concrete are simultaneously influenced by four major sources:

1. hydration and microstructural variation \((14)\),
2. changes in pore solution composition \((20,25)\),
3. moisture variation \((15,20,21)\), and
4. temperature variation \((26)\).

Due to the simultaneous influence of these factors, a single measurement of concrete conductivity is unable to provide reliable information describing material properties or performance. To overcome these limitations, the material sensing system described here provides a combination of four measurements (i.e., concrete conductivity, pore solution conductivity, relative humidity, and temperature). Simultaneous analysis of these four measurements provides sufficient calibration information to resolve the concurrent influences of pore solution, moisture content, and temperature variation. The final results enable measurement of the material’s microstructural properties as well as monitoring moisture and ion transport inside concrete.

3.0 THE DEVELOPED MATERIAL SENSING AND HEALTH MONITORING SYSTEM

The health monitoring system developed in this study consists of three electrical conductivity-based sensors and a temperature sensor. The electrical sensors include a concrete conductivity \((\sigma_t)\) sensor, a pore solution conductivity \((\sigma_o)\) sensor, and a conductivity-based relative humidity (RH) sensor. Figure 1 provides a schematic representation of this sensing system. A combined application of these four sensors enables the measurement and monitoring of (1) setting and hardening in fresh concrete; (2) microstructural and transport properties such as porosity, pore connectivity, water permeability, and ion diffusivity; (3) changes in the internal chemistry of the system (due to the hydration reactions, penetration of aggressive ions, or carbonation of concrete); and (4) internal humidity of concrete that can be used to monitor moisture movement, shrinkage, and the potential of moisture sensitive reactions such as ASR and corrosion inside concrete \((8)\). The temperature \((T)\) sensor enables monitoring the rate of hydration and strength development (i.e., maturity) of concrete while it provides information for temperature calibration of the electrical sensors. In addition, an acoustic/ultrasonic sensor can be coupled with this system to add the capacity of damage (i.e., crack) monitoring inside the material \((7)\).
4.0 BACKGROUND ON ELECTRICAL CONDUCTIVITY MEASUREMENTS OF CEMENT AND CONCRETE

Electrical conductivity of concrete is a material property obtained from the electrical resistance measured between two points (i.e., electrodes) inside the material. The measured resistance is normalized to account for the effects of specimen and electrode geometry:

\[
\sigma_t = \frac{k}{R_b}
\]

where \(\sigma_t\) (S/m) is the conductivity of concrete, \(R_b\) (\(\Omega\)) is the measured resistance and \(k\) (1/m) is a geometry factor that is calculated or measured experimentally (25). The electrical resistance of concrete can be obtained from direct current (DC) or alternating current (AC) measurements. The use of AC measurements is frequently preferred, however, due to difficulties associated with polarization effect and permanent microstructural changes induced by DC measurements (27). Electrical impedance spectroscopy (EIS) is a method in which an alternating (AC) voltage is applied to a specimen and the measured current and phase lag are related to the specimen’s real and imaginary impedances (14,28). This impedance response is used to obtain several electrical properties of the specimen including its bulk resistance \(R_b\).

The conductivity of concrete is related to the properties and distribution of the material’s constituent phases. Concrete can be considered as a composite material containing solid (e.g., unhydrated cement, hydration products, aggregates), liquid (i.e., pore solution), and vapor (e.g., air voids, dried capillary and gel pores) phases (27). The liquid phase is an ionic electrolyte (containing \(Na^+\), \(K^+\), \(Ca^{2+}\), \(OH^-\), \(SO_4^{2-}\), and often \(Cl^-\) ions) and as such, it is electrically conductive. The conductivity of the liquid phase typically varies in the range of \(\sigma_o = 1\) S/m to \(\sigma_o = 20\) S/m depending on the concentration of ions (27,29). The solid and vapor phases are essentially non-conductive as the conductivity of the solid phase can be approximated as \(\sigma_s \approx 10^{-9}\) S/m while air has a conductivity of approximately \(10^{-15}\) S/m (27). As a result, the flow of electricity inside concrete is essentially ionic and through the material’s liquid phase (i.e., pore solution).
A modified parallel law is frequently used to model the electrical conductivity of hardened cement paste and concrete (13,14):

\[ \sigma_t = \sigma_o \phi \beta \]  

(2)

where \( \sigma_t \) (S/m) is the conductivity of cement paste or concrete, \( \sigma_o \) (S/m) is the conductivity of pore solution, and \( \phi \) and \( \beta \) (both unitless) are respectively, the volume fraction and connectivity of the material’s liquid phase. Connectivity (\( \beta \)) is a parameter that accounts for the effective length and size variation of the conduction paths (i.e., liquid filled pores) (27,30). It has been shown (31) that, in a hydrating cement paste, changes in the liquid connectivity (\( \beta \)) are more significant than changes in the conductivity and the volume fraction of the liquid phase.

The conductivity of concrete (\( \sigma_t \)) can be related to its microstructural and transport properties (as described in the next section); however, for this purpose, knowledge of the pore solution conductivity (\( \sigma_o \)) is necessary (13,14). In addition to its dependence on the conductivity (\( \sigma_o \)), volume fraction (\( \phi \)), and connectivity (\( \beta \)) of the liquid phase, concrete conductivity is influenced by moisture and temperature variation. Drying causes a significant change in the volume fraction and connectivity of the liquid phase and as such, can influence the conductivity of concrete by several orders of magnitude (29). The temperature dependence of electrical conductivity has been studied by several researchers (26,32-34) and was found to be mainly due to the dependence of the mobility of ions on the temperature of the material. Meanwhile, temperature changes can influence the solubility of ions and may also cause microstructural changes in concrete especially at early ages. A simultaneous measurement of concrete conductivity, pore solution conductivity, relative humidity (or moisture content), and temperature is required to account for these concurrent changes.

5.0 APPLICATIONS OF THE CONCRETE CONDUCTIVITY (\( \sigma_t \)) SENSOR

The concrete conductivity (\( \sigma_t \)) sensor is comprised of two parallel electrodes that are embedded inside concrete (cement) at a certain distance from each other. In this study, 2.5 mm diameter stainless steel rods were used at a 10 mm center to center distance (Figure 2). The electrical resistance is measured between these electrodes and the electrical conductivity (\( \sigma_t \)) is computed using equation (1). The measured conductivity is used for three main applications: (1) monitoring the time of setting, (2) measurement of microstructural properties (such as porosity and pore connectivity), and (3) estimation of the material’s transport properties including water permeability and ion diffusivity. These applications are described in the following sections in greater details.

5.1 Background on the Three Applications of the \( \sigma_t \) Sensor

5.1.1. Measurement of the Time of Setting

Perhaps, measurement of setting is one of the oldest applications of electrical conductivity measurement in concrete. Shimizu (35) correlated an inflection point in the conductivity versus age curve with the setting time of a series of cement paste specimens. Later, Calleja (36) confirmed that setting time could be determined with electrical measurements and illustrated the influence of frequency on the measured response. McCarter and Afshar (37) and Perez-Pena et al. (38) described the relationship between the conductivity and the rate of heat evolution for several types of cement pastes. More recently, Backe et al. (39) used a similar approach to monitor the hardening process of oil-well cement slurries.
5.1.2. **Measurement of Microstructural Properties**

The electrical conductivity of concrete is related to its microstructural properties (e.g., porosity and pore connectivity) through the use of the modified parallel law; equation (2) (13,14). The inverse of the product $\phi \beta$ (porosity × connectivity) is often referred to as the microstructure’s formation factor ($F$; unitless) in the literature (30):

$$F = \sigma_o / \sigma_t = 1 / \phi \beta$$

(3)

The formation factor ($F$) is the lumped effect of the microstructure on the electrical conductivity of the material which includes both the contributions of the volume fraction available for conduction ($\phi$) and the topology of conducting paths ($\beta$) (30).

5.1.3. **Measurement of Transport Properties**

Similar to ionic conduction, ionic diffusion is a transport mechanism associated with the random walk of charged species. The main difference between the two is the driving force behind the transport phenomenon. While electrical conduction is driven by the presence of an electrical potential between two points inside the material, diffusion is driven by a chemical potential (i.e., concentration gradient). Garboczi (13) provided a formula similar to the modified parallel law (equation (2)) to describe ionic diffusion inside concrete:

$$D = D_o \phi \beta$$

(4)

where $D$ (m$^2$/s) is the effective diffusion coefficient of a specific substance (e.g., sodium chloride) inside the material, and $D_o$ (m$^2$/s) is the diffusion coefficient of that substance through pore fluid. Atkinson and Nickerson (40) suggested a similar relationship (also known as the Nernst-Einstein equation) for calculation of the ionic diffusivity ($D$):

$$D = D_o \left( \sigma_t / \sigma_o \right) = D_o \left( \frac{1}{F} \right)$$

(5)

where $F$ is the formation factor as defined by equation (3).

Christensen et al. (14) showed that the results obtained from equation (5) are in reasonable agreement with the traditional measurements of diffusivity. Meanwhile, applications of equation (5) offer significant advantages over the traditional measurements of diffusivity including the simplicity, time efficiency, and non-destructive nature of electrical measurements, as well as the possibility of testing concrete at early-ages.

Meanwhile, Katz and Thompson (41) suggested that the hydraulic permeability of porous rocks can be described as a function of the material’s formation factor provided that a characteristic length scale of the pore structure is also known:

$$k = \frac{1}{226} d_C^2 \left( \sigma_t / \sigma_o \right) = \frac{1}{226} d_C^2 \left( \frac{1}{F} \right)$$

(6)

where $k$ (m$^2$) is the effective permeability, and $d_C$ (m) is the characteristic pore size (i.e., the pore diameter that dominates fluid transport). Katz and Thompson (41) suggested using the threshold pore diameter obtained from Mercury Intrusion Porosimetry (MIP) measurements for the value of $d_C$. Further, they showed that equation (6) provides good agreement with experiments across a broad range of permeabilities. Christensen et al. (42) applied equation (6) for calculation of the water permeability of several types of cement pastes and obtained good agreement with experiments.
5.1.4. **Summary of the Present Study**

In this work, the electrical conductivity of two types of cement paste is measured (using the $\sigma_t$ sensor) as a function of specimen age. The results are compared with the rate of hydration measurements (obtained from the chemical shrinkage ($43$)) and used to monitor the setting and hardening of the material. By separately measuring the pore solution conductivity ($\sigma_o$), the material’s formation factor ($F$) and the chloride diffusion coefficient ($D$) are determined as a function of age. When analyzing the measured conductivity, a knowledge of pore solution conductivity, moisture content (or humidity), and temperature is necessary.

5.2 **Materials, Specimens, and Testing Procedures**

Two types of cement pastes were prepared: a plain cement paste with $w/c = 0.30$ and a cement paste with $w/c = 0.30$ for which $5\%$ of water was replaced with a commercially available shrinkage reducing admixture (Tetraguard AS-20, manufactured by Degussa Admixtures). Type I ordinary portland cement with a Blaine fineness of $360 \text{ m}^2/\text{kg}$ and a Bogue phase composition of $60\% \text{ C}_3\text{S}$, $12\% \text{ C}_2\text{S}$, $12\% \text{ C}_3\text{A}$, $7\% \text{ C}_4\text{AF}$ and a $\text{Na}_2\text{O}$ equivalent of $0.72\%$ was used. To enhance the consistency and workability of the mixtures, a high range water reducer (Glenium 3000NS, produced by Degussa Admixtures) was added to both mixtures at a rate of $0.5\%$ by weight of cement.

De-aired, plain cement pastes were prepared using de-ionized water according to the procedure described in ($31$) (de-aired specimens were needed for proper measurement of the chemical shrinkage as discussed below).

Conductivity of the two cement paste mixtures was measured as a function of age using the $\sigma_t$ sensor embedded inside cylindrical specimens (22 mm diameter and 50 mm height); as shown in Figure 2. Stainless steel electrodes were embedded longitudinally inside cylindrical plastic vials (i.e., molds) before casting the cement paste. The bulk resistance ($R_b$) was measured using a Solartron 1260 Impedance Gain-Phase analyzer. A $100 \text{ mV}$ AC stimulus was applied to the specimen over the frequency range $10 \text{ MHz}$ to $1 \text{ Hz}$ (10 steps/frequency decade). Nulling was performed according to ($14$) to account for the induction effect of the lead wires. The conductivity ($\sigma_t$) was obtained from the measured bulk resistance ($R_b$) (equation (1)) using a geometry factor $k = 18.11 /\text{m}$ which was determined experimentally ($25$). Conductivity was measured at 20 minute intervals from 35 minutes after cement came in contact with water and up to the age of 48 hours.

![FIGURE 2 Setup for measurement of the conductivity of cement paste; (a) sealed cylindrical specimen, (b) water container for isothermal curing](image-url)
During the measurements, the specimens remained sealed inside plastic vials to prevent moisture loss. Each of the sealed plastic vials was partially immersed in a water container at 23 °C to maintain the specimen’s temperature constant during the test period (Figure 2). No moisture or temperature calibrations were needed for these specimens. However, when moisture or temperature variations are expected, calibration of the measured conductivity is required according to the procedure described by (27).

On the other hand, to obtain the microstructural and transport properties, knowledge of the pore solution conductivity ($\sigma_o$) is essential. In the work presented here, pore solution was extracted from companion paste specimens and used for the measurement of solution conductivity ($\sigma_o$). Alternatively, results from the pore solution conductivity ($\sigma_o$) sensor (Section 6.0) can be employed.

Pore solution was extracted using pressure filtration or a high pressure steel die. Pressure filtration was performed for specimens in the plastic phase (10 and 30 minutes, 1, 3, and 6 hours after water addition) according to the procedure of (44). For hardened specimens, a high pressure extraction die with a capacity of 550 MPa was used according to (45). After extraction, pore solution was stored in small (2.5 cc) plastic containers and sealed immediately to prevent carbonation. Pore solution conductivity ($\sigma_o$) was measured using a conductivity meter connected to the impedance analyzer.

To monitor the rate of hydration, chemical shrinkage of each mixture was measured as a function of age according to the buoyancy principle using the procedure outlined in (43) for a 25 g specimen with 10 g of surface water. The time of initial and final setting was determined using the Vicat needle according to the procedure described by ASTM C191.

### 5.3 Results

#### 5.3.1 Time of Setting

The results of chemical shrinkage measurements, $CS$ (ml/g cement), are provided in Figure 3 for the two cement pastes. The rate of chemical shrinkage, $dCS/dt$ (ml/g cement/hr), was obtained and used as an indication of the rate of hydration. The curves representing the rate of chemical shrinkage can be used to identify the five phases of hydration (initial hydrolysis, dormant, acceleration, deceleration, and steady state periods) (46). Based on the rate of chemical shrinkage ($dCS/dt$), the time corresponding to the end of dormant period was approximately determined as 5 hours for the paste with w/c = 0.30 and 6 hours for the paste with w/c = 0.30+5%SRA. In addition, initial and final setting was measured (according to ASTM C191) and the results are presented in Figure 3. A slight reduction in the magnitude of chemical shrinkage and a delay in set are observed in the mixture containing SRA. This is attributed to a retarding effect of SRA (47).

The measured conductivity, $\sigma_t$ (S/m), and the rate of conductivity, $d\sigma_t/dt$ (S/m/hr), are shown in Figure 4. Initially (up to 1.5 hours for the w/c = 0.30 paste and up to 2.5 hours for the w/c = 0.30+5%SRA paste), conductivity is increasing; mainly due to a simultaneous increase in the pore solution conductivity (see Figure 5 (a)). As such, the rate of electrical conductivity ($d\sigma_t/dt$) is positive during these early hours. Shortly, however, the rate of conductivity decreases and this is followed by a time period during which the rate is approximately constant. This time period was observed to be between 2.5 and 5 hours for the paste with w/c = 0.30 and between 3 and 6 hours for the paste containing SRA.
During the dormant period, the rate of hydration and microstructure development is minimal. As such, it is expected that the rate of electrical conductivity remains constant and close to zero. This is, in fact, observed in Figure 4 as the region of constant rate of conductivity (as described above). The end of this time period is observed to be in good agreement with the end of dormant period as determined from the chemical shrinkage measurements.
Meanwhile, the rate of conductivity \( (d\sigma_t/dt) \) exhibits a sharp peak that is observed to be in the vicinity of the time of final set. At final set, a percolated network of solid particles has formed that is capable of carrying mechanical loads. It is hypothesized that the formation of this percolated solid network alters the kinetics of microstructure development and causes a reduction in the rate of electrical conductivity which shows itself as a peak in the \( d\sigma_t/dt \) graph (31). Currently, further research is being performed using computer simulation of hydrating cement systems to observe whether the percolation of solids always corresponds with a peak in the rate of conductivity. The results are compared for several cement paste systems with varying particle size and water to cement ratio.

5.3.2. Microstructural Properties

Pore solution conductivity \( (\sigma_o) \) was measured from solutions extracted from companion specimens. Figure 5 (a) shows the measured values for the two paste mixtures. The pore solution conductivity \( (\sigma_o) \) was found to be consistently smaller for the paste containing SRA. Rajabipour et al. (47) discussed that this reduction in the conductivity of pore solution is in agreement with the results of chemical analysis of pore solution which shows lower ion concentrations in the pore solutions containing SRA.

The microstructure’s formation factor \( (F) \) is calculated for both materials using equation (3) by knowing the paste conductivity and the pore solution conductivity as a function of age. It is observed in Figure 5 (b) that the formation factor for the paste with SRA is consistently lower than the plain paste indicating a retarding affect of SRA. This is in agreement with the results of chemical shrinkage and the setting time described earlier.

FIGURE 5 (a) Pore solution conductivity \( (\sigma_o) \); (b) formation factor \( (F) \) and chloride diffusion coefficient \( (D) \); all as a function of specimen age
5.3.3. Transport Properties
The chloride diffusion coefficient of each material was calculated using the Nernst-Einstein equation (5) by knowing the formation factor as a function of age. A value of $D_o = 1.484 \times 10^{-9}$ m$^2$/s was used as for the diffusion coefficient of sodium chloride inside pore solution (48). The results (Figure 5 (b)) show a significant reduction in the chloride diffusivity of the materials during the first 48 hours of hydration.

Hydraulic permeability can be determined similarly using the Katz – Thompson equation (6) when the threshold pore diameter is separately measured or estimated. The obtained values of ion diffusivity and water permeability can further be used as input parameters of life-cycle simulation models to evaluate the long-term performance of the materials.

6.0 PORE SOLUTION CONDUCTIVITY ($\sigma_o$) AND RELATIVE HUMIDITY (RH) SENSORS
Both the $\sigma_o$ and RH sensors are conductivity-based sensors that are made from a porous material with known microstructural properties (in this study, a natural porous siltstone was used (27)). The porous sensor is saturated with an ionic solution (i.e., electrolyte) and then embedded inside concrete (the sensors are placed inside the formwork before pouring the concrete). Once embedded, the measured electrical conductivity of the sensor reflects the humidity and pore solution conductivity of the surrounding concrete.

The pore solution conductivity ($\sigma_o$) sensor (Figure 6 (a)) is in direct contact with concrete. As such, the solution inside the sensor comes to chemical equilibrium (i.e., ion concentrations) with the pore fluid of the surrounding concrete. Accordingly, a measurement of the conductivity of the sensor ($\sigma_o$) can be used to determine the conductivity of concrete’s pore solution. Rajabipour and Weiss (29) obtained a linear relationship between the conductivity of the siltstone and the pore solution conductivity; Figure 6 (b). The conductivity measurements need to be calibrated to account for the influence of temperature and humidity inside concrete.

![Diagram of sensor components](image)

**FIGURE 6** (a) Pore solution conductivity ($\sigma_o$) sensor (top) and Relative humidity (RH) sensor (bottom); (b) Calibration curve for $\sigma_o$ sensor; (c) Calibration curve for RH sensor
The relative humidity (RH) sensor (Figure 6 (a)) works based on the relationship between the moisture content of a porous material and its electrical conductivity (29). The sensor is enclosed with a membrane that only allows vapor transport between the sensor and the surrounding concrete. When embedded, the relative humidity inside the membrane comes to equilibrium with the humidity of the concrete. As such, a measurement of the conductivity of the sealed sensor ($\sigma_{RH}$) can be used to determine the relative humidity of the surrounding concrete (Figures 6 (c)). The conductivity measurements need to be temperature calibrated prior to the determination of humidity.

7.0 SUMMARY AND CONCLUSIONS

A new material sensing and health monitoring system is described that is capable of insitu measurement of several concrete material properties and state parameters (e.g., internal humidity, ion concentrations). The measurements from this system provide input parameters required for performance predictions of concrete structures. The sensing system is comprised of three electrical conductivity-based sensors and a temperature sensor. It was shown that this system can be used to:

- monitor setting and hardening; determination of the time of final set,
- measure microstructural properties (porosity, connectivity, and formation factor), and
- measure transport properties (including chloride ion diffusivity and water permeability).

Measurements of the $\sigma_t$ sensor were used to compare hydration and microstructure development of two cement paste mixtures at early ages. It was shown that this sensor enables a rapid, insitu, and non-destructive measurement of transport properties of the material. Also, a brief description of the pore solution conductivity ($\sigma_o$) and relative humidity (RH) sensors were included. It was discussed that these sensors can provide the capacity of monitoring the internal chemistry of the system and monitoring moisture transport inside the material.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge support received from the National Science Foundation (NSF) under Grant No. 0134272: a CAREER AWARD granted to the last author. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. This work was conducted in the Materials Characterization and Simulation Laboratory at Purdue University; as such the authors acknowledge the support that has made this laboratory and its operation possible.

REFERENCES


