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USING EMBEDDED SENSORS TO MEASURE CONCRETE FORMATION FACTOR

AUTHORS

Amir Alarab, Penn State University

Kostiantyn Vasylevskyi, Callentis Consulting Group

Farshad Rajabipour, Penn State University

Robert Spragg, Federal Highway Administration

Nima Karagh-Ostadi, Callentis Consulting Group

Dan King, National Concrete Pavement Technology Center

SPONSOR

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National Concrete Pavement Technology Center
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
cptechcenter.org

Peter Taylor, Director
515-294-3230 / ptaylor@iastate.edu

National Concrete Pavement Technology Center

Iowa State University
Institute for Transportation

Background

Transportation agencies in the United States seek to implement new test methods and technologies that better predict the long-term durability of concrete materials. These methods are needed to support initiatives such as the performance-engineered mixtures (PEM) approach (AASHTO R 101) and ultimately to design and build durable concrete mixtures. Among the more popular test methods adopted in recent years are surface resistivity (AASHTO T 358) and bulk resistivity (AASHTO T 402).

These tests involve the application of an electrical current to a saturated concrete cylinder to measure the resistivity of the sample. This measurement characterizes the transport properties of the sample, i.e., how easily fluids and ions can pass through concrete. The resistivity measurement is sensitive to ions present in the pore solution of the concrete, which varies depending on the constituent materials used to create the mixture. Therefore, to obtain an objective measurement of transport properties, it is necessary to normalize the resistivity measurement by the concrete pore solution resistivity (PSR) to calculate the concrete formation factor (FF).

While concrete resistivity tests are rapid and easy to conduct, it has traditionally been difficult to accurately measure or estimate PSR. These difficulties may limit the ability to implement resistivity testing as a criterion for mixture qualification or acceptance, since without measuring PSR, it is not possible to account for the influence of the pore solution on the resistivity results.

Embedded Sensor System

To enable easier measurements of PSR and overcome the current limitations of resistivity testing, a team of researchers at Callentis Consulting Group and The Pennsylvania State University has developed a new embedded sensor system (Figure 1). The sensor system consists of a PSR sensor package, which is plugged into a placement frame, along with an optional set of frame stands to measure concrete mixture resistivity. The PSR sensor package includes a nanoporous matrix with insulated embedded electronics.

The sensor placement frame is inserted into a plastic cylinder mold, and a cylindrical concrete sample is cast with the embedded sensor inside. After 24 hours, the concrete sample is either left for sealed curing or demolded and transferred to a simulated pore solution, saturated lime water, or a moist curing room.

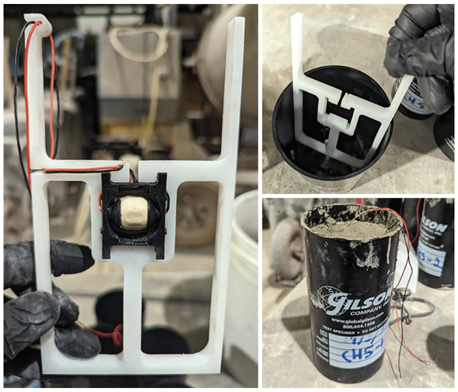

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Figure 1. Embedded sensor system, showing the sensor package and placement frame (left), the placement frame in an empty plastic cylinder mold (top right), and the cast concrete sample with the placement frame and sensor inside (bottom right)

After about 14 to 28 days (depending on the concrete mix design and curing conditions), the PSR sensor comes into ionic equilibrium with the pore solution of the concrete inside the cylinder.

To measure PSR, a benchtop or handheld LCR device is connected to wires that extend from the frame out of the hardened concrete cylinder, as shown in Figure 2. The device applies alternating current at a frequency of 100 kHz and measures the resistance of the PSR sensor. Accounting for the temperature of the cylinder and a calibration factor for the sensor, this measurement is used to calculate the PSR of the sample.

The placement frame can also include stands with stainless steel pins that allow for measurement of the concrete mixture resistivity using an LCR device or a Wenner probe (similar to the AASHTO T 358 surface resistivity test procedure). The embedded sensor system is therefore capable of measuring both the PSR and the mixture resistivity and providing a direct calculation of FF for the concrete mixture.

Demonstration

The Federal Highway Administration (FHWA) has sponsored the development of the embedded sensor system through the Small Business Innovation Research (SBIR) program, including verification and independent validation testing. To date, the results of these tests indicate that the PSR measurements taken by the embedded sensor system have demonstrated excellent repeatability (93% to 99%), as shown in Figure 3.

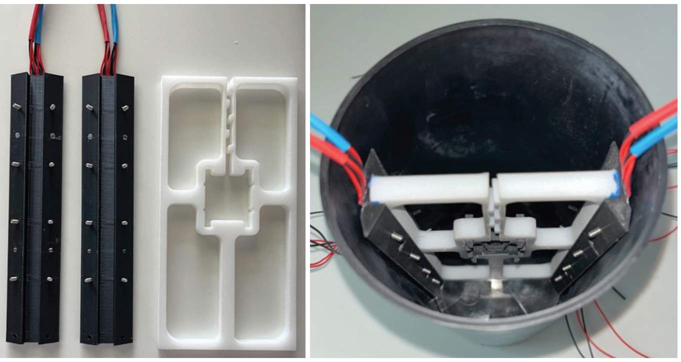

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Figure 2. Mixture resistivity probes and placement frame (left) and mixture resistivity probes attached to the placement frame inside an empty plastic cylinder mold (right)

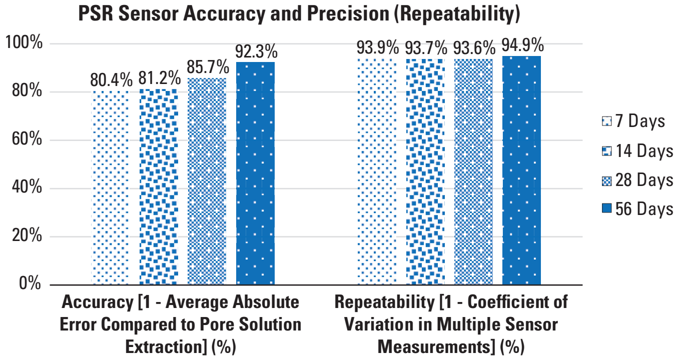

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Figure 3. Results of PSR sensor accuracy and precision (repeatability) tests

Meanwhile, the accuracy of PSR measurements obtained from the embedded sensor system compared to PSR measurements obtained from samples of pore solution extracted from companion cylinders has been promising, but results have varied depending on concrete age and the curing process used. PSR measurements obtained from the embedded sensor system inside concrete samples cured for 56 days in a simulated solution were 92% accurate compared to PSR measurements of a solution extracted from companion samples that were cured in the same simulated solution. The results indicate that ionic leaching from concrete into the curing solution can impact sensor measurements at later ages.

Next Steps and Future Activities

An investigation of differences between PSR measurements obtained from the embedded sensor system and from extracted pore solution has shown that the pore solution near the PSR sensor is different from the pore solution extracted from a whole companion concrete cylinder. The research team plans to develop simulation-based and experimentally verified methods for calculating volumetric average PSR for the entire cylindrical sample based on sensor measurements as a function of time and depending on the curing process.

Further experimentation is also planned for different types of concrete mixtures and curing alternatives to better establish the precision and bias of the embedded sensor system. These experiments will also be used to determine the optimum timing to calculate FF based on sensor measurements.

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