Electrical Resistivity of Concrete

Concepts, applications, and measurement techniques

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The so-called rapid chloride permeability (RCP) test is a widely accepted approach for assessing the durability of concrete. Originally proposed by Whiting[1] and since standardized as ASTM C1202[2] and AASHTO T 227,[3] the test method allows the measurement of the total electrical charge passing through a concrete specimen subjected to a standard voltage. While it does provide an indication of the concrete's ability to resist chloride ion penetration, the RCP method is neither rapid nor capable of direct measurement of chloride permeability. Rather, the test was developed by correlating a measured charge to the total chloride penetrating to a depth of 1-5/8 in. (41 mm) of reference slabs subjected to a 90-day ponding test (AASHTO T 259[4]). The chloride permeability categories are thus qualitative.

As an alternative, electrical resistivity measurement can be used for the performance-based evaluation of concrete. Resistivity test procedures, including sample preparation, are much easier and faster than that of the RCP test. Also, the resistivity value can be directly related to the chloride diffusion coefficient of concrete using the Nernst-Einstein equation.[5]

Several techniques have been developed and studied for measuring the electrical resistivity of concrete, including the bulk electrical resistivity and surface electrical resistivity. In this article, different approaches in the measurement of concrete electrical resistivity are discussed. The correlations between the resistivity measurements and certain durability characteristics of concrete are reviewed.

Electrical Resistivity

Electrical resistivity measurement techniques are becoming popular among researchers and scholars for the quality control and durability assessment of concrete (for example, refer to References 6 and 7). The adoption of these techniques into standards and guidelines has been rather slow, with only surface electrical resistivity adopted as a test method by the American Association of State Highway and Transportation Officials (AASHTO TP 95[8]).While ASTM Committee C09 is also developing a standard procedure for evaluating the surface electrical resistivity of concrete, the only resistivity test method that has been standardized to date is ASTM C1760,[9] and this is used for measuring the bulk electrical resistivity. Thus, a gap exists between the state-of-the art knowledge and the current industry practice.

The concepts

Durability of concrete depends largely on the properties of its microstructure, such as pore size distribution and the shape of the interconnections (that is, tortuosity). A finer pore network, with less connectivity, leads to lower permeability. A porous microstructure with larger degree of interconnections, on the other hand, results in higher permeability and reduced durability in general. The principal idea behind most electrical resistivity techniques is to somehow quantify the conductive properties of the microstructure of concrete. Overall, the electrical resistivity of concrete can be described as the ability of concrete to withstand the transfer of ions subjected to an electrical field. In this context, resistivity measurement can be used to assess the size and extent of the interconnectivity of pores.

Resistivity ρ is an inherent characteristic of a material, and is independent of the geometry of the sample. Equation (1) describes the relationship between the resistivity and resistance:

$$\rho = k \cdot R \tag{1}$$

where R is the resistance of concrete; and k is a geometrical factor which depends on the size and shape of the sample as well as the distance between the probes on the testing device. In practice, electrical resistance is directly measured by the testing device and resistivity is calculated from Eq. (1).

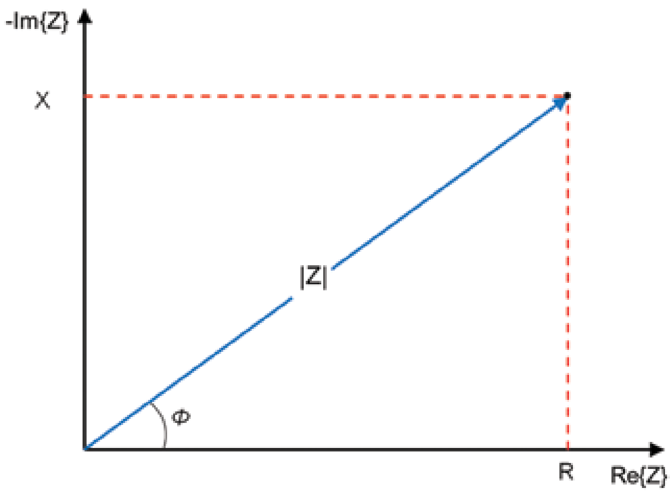

Fig. 1: Impedance is a complex number that can be represented as the vector sum of resistance on the real axis and reactance on the negative imaginary axis

Measurement

While the measurement of electrical resistance of concrete looks very simple at first glance, the complex microstructure of concrete makes it difficult to find a reliable technique. Concrete is a porous "composite" material, and depending on the moisture content (that is, the degree of the saturation of the pores), it may exhibit conductive or insulating characteristics. For example, a concrete sample might exhibit very high electrical resistance when it is dry, but the same concrete would have much lower resistance in a saturated condition. Moreover, concrete has capacitive properties, which means it can hold electrical charge. Because direct current (DC) can induce high polarization effects on the electrode-concrete interface as well as inside the specimen at the pore-solution to solid-phase interface, DC-based techniques fall short in eliminating the capacitance properties of concrete from measurements. When concrete is subjected to an AC current, however, the dipoles of ions in the pore solution position such that they can direct the electric current. Alternating current (AC) should therefore be employed to measure the electrical resistance of concrete, but this introduces reactance, a nonresistive opposition to current in an AC circuit, to the measurements.

Thus, the concept of "impedance" must be considered. Impedance Z represents the joint opposition to current resulting from resistance R and reactance X. Z is described as a complex number, and a geometric representation is established as the vector sum of R on the real axis and X on the orthogonal imaginary axis (Fig. 1). Z can also be represented by a magnitude $|Z|$ and a phase angle ø.

It's important to note that both $|Z|$ and ø vary with the frequency of the applied current. It also should be noted that only the normal resistance of concrete R can represent the ionic movement in the pore network and be correlated with the durability characteristics of concrete. Therefore, an appropriate electrical technique should be employed to minimize the capacitive response of concrete and accurately measure the normal resistance.

Measurement Techniques

Several configurations have been proposed to set up concrete in an electric circuit and perform the impedance measurements. Generally, the connection of the concrete to the circuit is provided by metal electrodes. The electrical response of such a system is normally determined with the aid of an equivalent circuit model representing the electrical properties of concrete and the electrode-concrete interface. Based on the proposed models, different measurement techniques have been developed, including two-point uniaxial and four-point (Wenner probe) techniques. Schematics of these test methods are shown in Fig. 2.

Uniaxial method

In this technique, the concrete sample is placed between two electrodes (usually two parallel metal plates) with moist sponge contacts at the interfaces to ensure a proper electrical connection (Fig. 2(a)). An AC current is applied, and the drop in the potential between the electrodes is measured. Equation (2) describes the geometrical factor used in the uniaxial technique:

$$k = \frac{A}{L} \tag{2}$$

where A is the cross-sectional area perpendicular to the current; and L is the height of a prismatic or cylindrical concrete sample. The resistivity can then be determined using Eq. (1). The uniaxial technique is a simple yet reliable method for measuring the bulk electrical resistivity in laboratory-based quality control tests. The same cylindrical concrete specimens prepared for the compression test can be used for resistivity measurement, and this nondestructive test takes only few seconds. However, the application of this test method for field evaluation is very limited, as it requires that concrete core samples are taken from the existing structure.

Four-point method

In this technique, the surface electrical resistivity of concrete is measured using four electrodes. One widely accepted setup is the Wenner probe, where the four electrodes are located in a straight line and equally spaced. The two inner electrodes measure the electrical potential V created when the exterior electrodes apply an AC current I to the concrete (Fig 2(b)). For a semi-infinite homogenous material, the geometrical factor is defined by Eq. (3)

$$k = \gamma a \tag{3}$$

where a is the distance between the electrodes (equally spaced); and γ is the dimensionless geometry correction factor. For semi-infinite concrete elements (for example, concrete slabs), γ is equal to 2π. This is not the case for tests conducted in a laboratory condition on small cylindrical or cubic

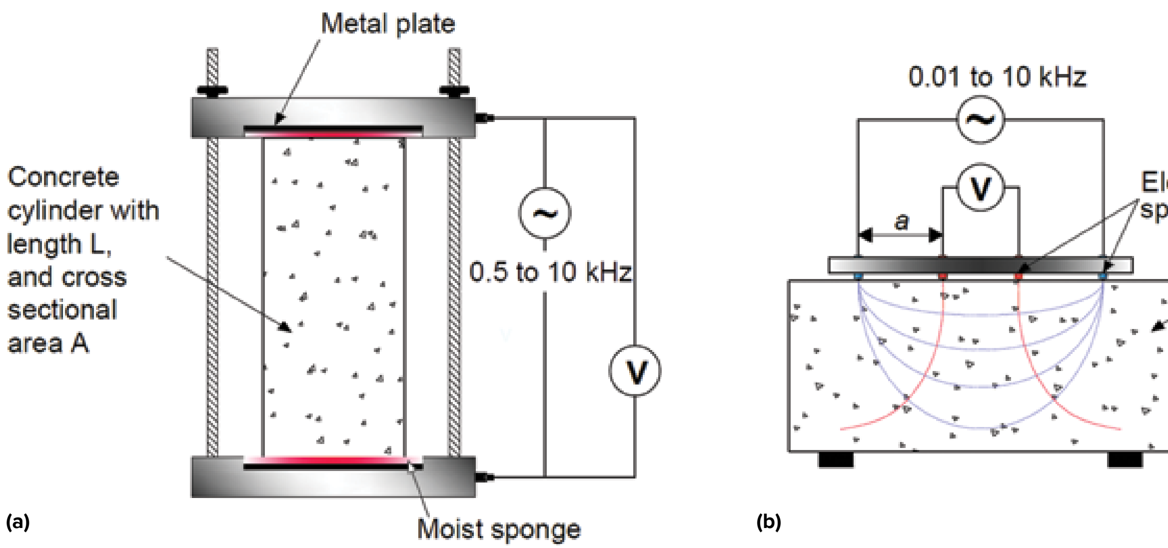

Fig. 2: Electrical resistivity measuring techniques: (a) two-point uniaxial method; and (b) four-point (Wenner probe) method

specimens. A different geometrical factor or an appropriate correction factor should be used to account for the effect of sample size for laboratory specimens[10]; otherwise, the resistivity will be overestimated.

AASHTO TP 95 specifies an electrode spacing of 1.5 in. (38 mm) with an AC frequency of 13 Hz. The effect of sample size is considered by specifying two different criteria for qualitative assessment of chloride ion penetration rather than the calculation of inherent resistivity of concrete via Eq. (3).

The four-point method is nondestructive, fast, and simple, and because of its configuration, this method is ideal for on-site evaluation of concrete. It should be noted that the presence of cracks and reinforcing bars in concrete can affect the measurements. Unlike the uniaxial technique, Wenner probe measurements are sensitive to the surface condition of the concrete, including the presence of moisture and voids, which is why multiple measurements around the specimen (eight times as per AASHTO TP 95 test method) are required to obtain a reliable average for the inherent resistivity of concrete.

What Influences the Measurements?

The inherent electrical resistivity of concrete is affected by the pore size distribution and interconnection, conductivity of pore fluid, degree of saturation, and temperature. The electrode contact properties and the signal frequency can also affect the measurements. However, if the effects of these factors are appropriately taken into account, any resistivity measurement technique should deliver the same resistivity value.

Degree of saturation

A change in the degree of saturation will affect the resistivity (or conductivity) of concrete as it would vary the amount of fluid in pore network. It is advisable to use a consistent curing method and ensure that the test specimens are in saturated surface dry (SSD) condition at the time of testing to make reliable and repeatable electrical resistivity measurements for quality control applications.

Temperature

The electric current flow in concrete is the result of ionic movement within the pore solution, and ionic mobility is affected by temperature. In general, an increase in the temperature increases ionic mobility, which in turn decreases the electrical resistivity. It has been reported that a temperature change of 1.8°F (1°C) can result in a 3% change in electrical resistivity of concrete.[11] Therefore, it is important to monitor temperature changes when testing concrete samples for electrical resistivity.

Signal frequency

The general representation of the impedance spectrum consists of two arcs in high- and low-frequency ranges (Fig. 3). While the characteristics of this spectrum at higher frequencies are attributed to the microstructure of concrete, the characteristics in low frequency region are primarily influenced by conditions at the electrode-concrete interface.

In the uniaxial method, resistivity measurements can be carried out at the frequency range of 0.5 to 10 kHz to obtain a relatively good representation of the real resistance of concrete. However, there is no general statement on the optimum frequency, as it varies with mixture proportions and moisture conditions. Figure 4 shows a relationship between resistivity measurements using two different signal frequencies (40 Hz and 1 kHz) in the uniaxial method. The use of a low-frequency signal (40 Hz) increased the measured resistivity by 9% compared to 1 kHz signal. So, in the uniaxial technique, the resistivity measurement at low frequencies (below 500 Hz) yields generally overestimated results due to the electrode-concrete contact interface effect. The effect of electrode-contact is less dominant in the Wenner probe method than in the uniaxial method and therefore, measurements can be conducted in a wider frequency range (10 Hz to 10 kHz).

Applications

Electrical resistivity is well correlated with certain performance characteristics of concrete such as chloride diffusion coefficient, water absorption, and corrosion rate of embedded steel. The technique also shows promise as a quality assurance tool for fresh and hardened concrete.

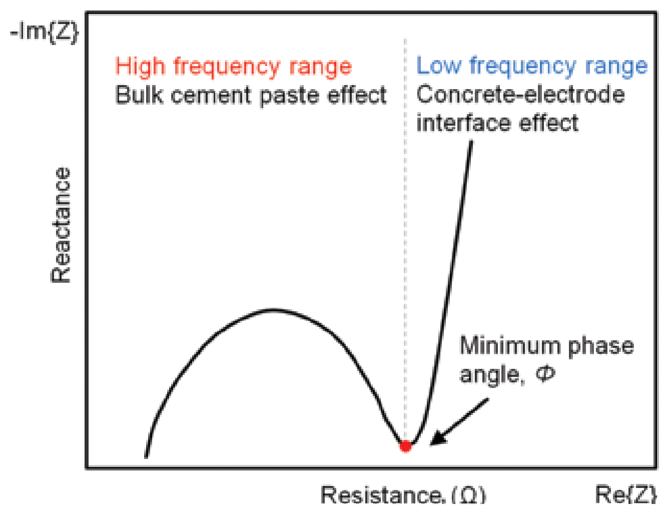

Fig. 3: Schematic representation of the AC Impedance response of concrete

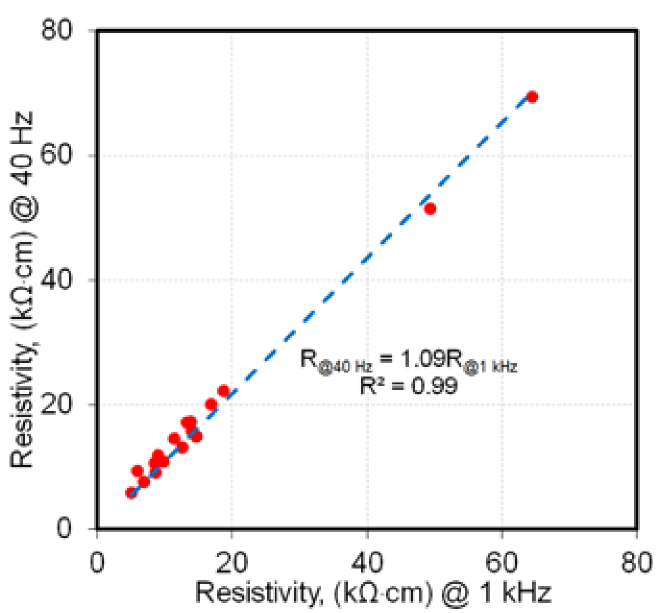

Fig. 4: A demonstration of the effect of signal frequency on bulk resistivity measurement: measurements taken at a low signal frequency of 40 Hz overestimated the resistivity by 9% relative to measurements taken at a signal frequency of 1 kHz

Chloride permeability measurement

Electrical resistivity can be used as a measure of concrete resistance to chloride penetration. Similar to the RCP test, electrical resistivity measurement can be used in the evaluation of ionic mobility within the pore solution of concrete. The RCP test was originally developed to quantify the chloride penetrability based on the electric charge Q passed through concrete over a specific period of time t. Based on laboratory experiments, Whiting[1] proposed different categories for the chloride permeability of concrete samples based on the electric charge passed through concrete (Table 1).

The electric current I is the flow of the electric charge Q over time t. The relation between electric charge and resistivity, therefore, can be expressed as Eq. (4):

$$Q = I \cdot t = \frac{V}{R} \cdot t = \frac{V}{\frac{L}{A}\rho} \cdot t = \underbrace{\left(\frac{V \cdot A \cdot t}{L}\right)}_{\text{constant}} \cdot \frac{1}{\rho} \tag{4}$$

Based on this equation, one can see that there is an inverse relation between passed charged Q and resistivity ρ. In other words, the relation between Q and conductivity is linear; however, the experiments show that there is a nonlinear relationship between conductivity and electric charge (Fig. 5). The reason for this nonlinear response is related to the generation of heat and increase in the ionic concentration of the pore solution of concrete by chloride penetration during the test. Both of these phenomena decrease the resistivity of concrete but not necessarily change the pore structure or resistance of concrete against chloride permeability.

Diffusion coefficient measurement

The diffusion coefficient of concrete is an important factor in the service life design of new structures, as well as for the maintenance and rehabilitation of existing structures. As

Table 1:
Comparison of chloride penetrability levels established for standards based on electrical resistivity (AASHTO TP 95) and charged passed (ASTM C1202)

Chloride ion penetrability	AASHTO TP 95,* kΩ·cm	ASTM C1202, coulombs
High	<12	>4000
Moderate	12 to 21	2000 to 4000
Low	21 to 37	1000 to 2000
Very Low	37 to 254	100 to 1000
Negligible	>254	<100

*4 x 8 in. (100 x 200 mm) concrete cylinder

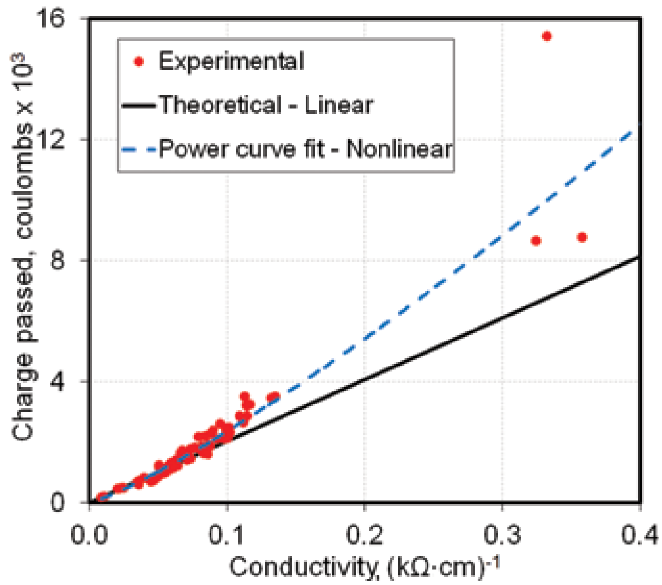

Fig. 5: Experimental and theoretical relationships between RCP and conductivity test results

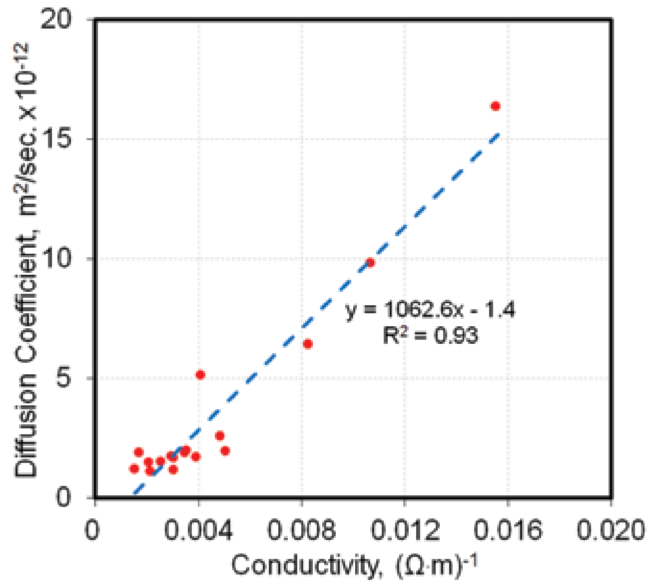

Fig. 6: Relationship between electrical conductivity and chloride diffusion coefficient based on measurements conducted on 20 different concrete mixtures

described in the Nernst-Einstein equation, the diffusion coefficient has a linear relationship with electrical resistivity of concrete in SSD condition (Fig. 6). The resistivity, therefore, can be used as a reliable technique to obtain the diffusion coefficient of concrete required in the service life estimation of structures.

Corrosion measurement

Investigations have found correlations between concrete resistivity and both the corrosion initiation and the propagation period. The corrosion rate often has an inverse correlation to the electrical resistivity of concrete. Hornbostel et al.[12] have compiled a comprehensive literature review on the relation of corrosion rate and electrical resistivity as well as the contributing factors. In general, higher electrical resistivity of concrete lowers the risk and the rate of corrosion.

Crack detection

The presence of cracks in the microstructure of concrete can change the transport properties of concrete. Cracks change the connectivity of pore structure, therefore the electrical properties of concrete. The electrical resistivity technique can also be used to detect and monitor the initiation and propagation of cracks in concrete. The development of microcracks in cementitious composite materials under tensile test was accurately determined by Ranade et al.[13]

Setting time measurement

The concept of electrical resistivity has been used to develop test methods for determining the setting time of cement mortars and concrete. As the fresh concrete sets and hardens, depercolation (discontinuity) of the capillary pore space increases the electrical resistivity. Bentz et al.[14] studied the feasibility of using electrical resistivity technique for predicting the setting time of cement paste and concrete mixtures.

Moisture content

Another potential application of the electrical resistivity method is to determine the moisture content of concrete. Rajabpour et al.[15] investigated the use of resistivity measurement in assessing the moisture content of concrete. However, the application and reliability of the method to determine the moisture content has yet to be evaluated.

Conclusions

Electrical resistivity measurement shows promise as a quality control and performance assessment tool for concrete materials. Both the uniaxial and the Wenner probe techniques provide consistent results if the appropriate geometry factors are used. While the uniaxial method is convenient for testing concrete samples or drilled cores, the Wenner probe method is a better choice for on-site evaluation.

The nonlinear relationship between electrical resistivity and RCP values is largely the result of changes in the temperature and properties of the pore solution during the RCP test. A relationship between electrical resistivity and diffusion coefficient would be more appropriate for quantifying the criteria required for the durability-based quality control of concrete, particularly those required for the classification of chloride permeability of concrete.

References

1. Whiting, D., "Rapid Determination of the Chloride Permeability of Concrete," *Report No*. FHWA/RD-81/119, Federal Highway Administration, Washington, DC, 1981, 174 pp.

2. ASTM C1202-12, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration," ASTM International, West Conshohocken, PA, 2012, 8 pp.

3. AASHTO T 277, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride," American Association of State Highway and Transportation Officials, Washington, DC, 2007, 12 pp.

4. AASHTO T 259, "Method of Test for Resistance of Concrete to Chloride Ion Penetration," American Association of State Highway and Transportation Officials, Washington, DC, 2006, 3 pp.

5. Lu, X., "Application of the Nernst-Einstein Equation to Concrete," *Cement and Concrete Research*, V. 27, No. 2, Feb. 1997, pp. 293-302.

6. Nadelman, E.I., and Kurtis, K.E.," A Resistivity-Based Approach to Optimizing Concrete Performance," *Concrete International*, V. 36, No. 5, May 2014, pp. 50-54.

7. Claisse, P.A., "Letter: Using Electrical Tests as Durability Indicators," *Concrete International*, V. 36, No. 10, Oct. 2014, p.17.

8. AASHTO TP 95, "Standard Test Method for Surface Resistivity of Concrete's Ability to Resist Chloride Ion Penetration," American Association of State Highway and Transportation Officials, Washington, DC, 2014, 10 pp.

9. ASTM C1760-12, "Standard Test Method for Bulk Electrical Conductivity of Hardened Concrete," ASTM International, West Conshohocken, PA, 2012, 5 pp.

10. Morris, W.; Moreno, E.I.; and Sagüés, A.A., "Practical Evaluation of Resistivity of Concrete in 433 Test Cylinders Using a Wenner Array Probe," *Cement and Concrete Research*, V. 26, No. 12, 1996, pp. 1779-1787.

11. Elkey, W., and Sellevold, E.J., *Electrical Resistivity of Concrete*, Norwegian Road Research Laboratory, Oslo, Norway, 1995, 33 pp.

12. Hornbostel, K.; Larsen, C.K.; and Geiker, M.R., "Relationship between Concrete Resistivity and Corrosion Rate—A Literature Review," *Cement and Concrete Composites*, V. 39, May 2013, pp. 60-72.

13. Ranade, R.; Zhang, J.; Lynch, J.P.; and Li, V.C., "Influence of Micro-Cracking on the Composite Resistivity of Engineered Cementitious Composites," *Cement and Concrete Research*, V. 58, 2014, pp. 1-12.

14. Bentz, D.P.; Snyder, K.A.; and Ahmed, A.M., "Anticipating the Setting Time of High-Volume Fly Ash Concretes Using Electrical Measurements: Feasibility Studies Using Pastes," *Journal of Materials in Civil Engineering*, July 2014, 6 pp.

15. Rajabipour, F.; Weiss, J.; and Abraham, D.M., "In-situ Electrical Conductivity Measurements to Assess Moisture and Ionic Transport in Concrete," *International RILEM Symposium on Concrete Science and Engineering: A Tribute to Arnon Bentur*, K. Kovler, J. Marchand, S. Mindess, and J. Weiss, eds., RILEM Publications SARL, 2004, 260 pp.

Selected for reader interest by the editors.

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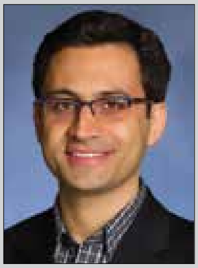

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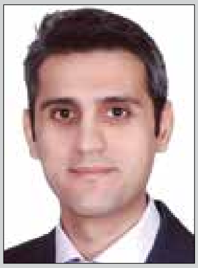

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