Electrical Resistivity—Its Role in Concrete Durability and Quality Control

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Concrete bridge components play a vital role in the development of long-lasting, durable bridges. The concrete used in precast and cast-in-place concrete components helps protect the reinforcement from the elements, especially chloride-containing deicing/anti-icing salts and saltwater. Concrete that is the most resistant to the ingress of salt from the environment has low porosity (for example, a low water-cement ratio [*w/c*]) and low pore interconnectivity.[1] The use of supplementary cementitious materials (SCMs) such as fly ash, silica fume, natural pozzolans, or slag generally does not reduce the overall porosity significantly; however, it can refine the pore structure to reduce pore connectivity.[1–3] As a result, the use of SCMs generally increases concrete resistance to fluid and salt ingress.

Questions exist about how to determine the resistance of a material to the ingress of chloride-containing salt and how to specify these materials. The rapid chloride permeability test (RCPT) is commonly used to quantify the resistance of a material to salt (chloride ingress).[4,5] It requires making cylinders, cutting them at the testing age, conditioning them by vacuum saturation, and exposing them to an electrical current for 6 hours. This test is destructive, and, like all testing, it has associated costs and reported errors, which, for this test method, are particularly associated with the use of electric potential.[6–8] The RCPT provides an indication of the electrical conductivity of the tested specimen, rather than its ionic transport properties. Salt-ponding tests can also be used, but these tests are destructive, time consuming, and costly, and they only correspond to one type of salt and salt concentration under ponding conditions.[9,10]

Figure 1. Test geometries used to measure the electrical resistivity of concrete. Figure: Oregon State University, adapted from Spragg et al. (2013).[10]

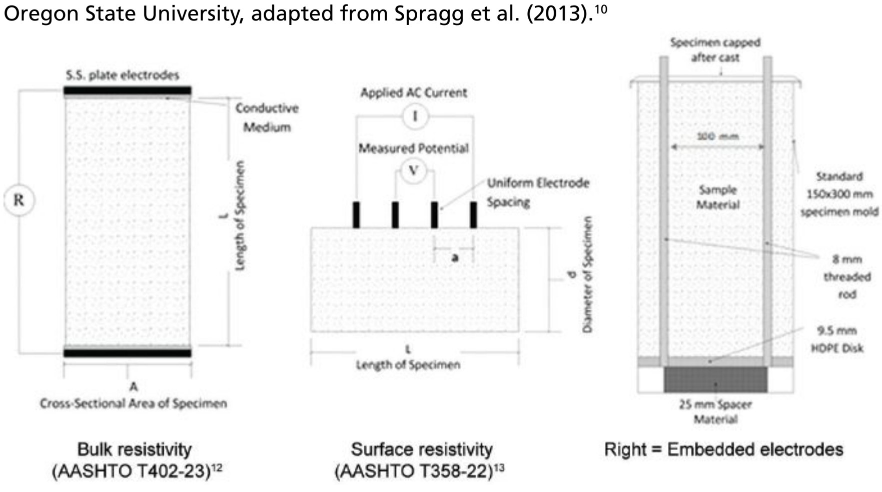
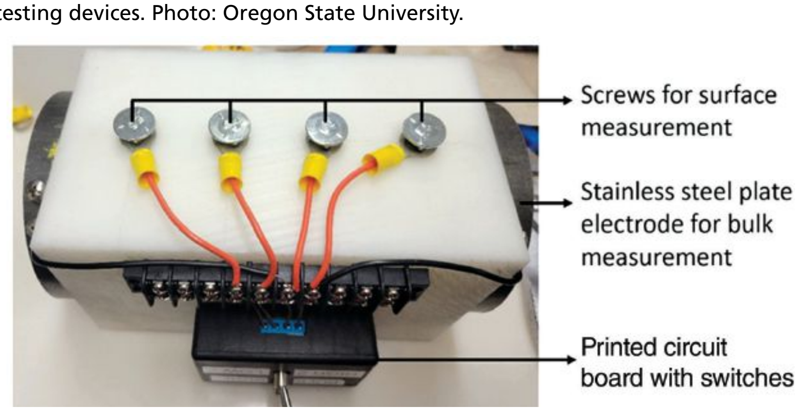


Figure 2. Verification device used to train users and evaluate the bias of commercial testing devices. Photo: Oregon State University.



An alternative measure of transport—part of the American Association of State Highway and Transportation Officials' (AASHTO's) publication R 101[11]—measures the electrical resistivity of concrete using bulk resistivity (AASHTO T402-23),[12] surface resistivity (AASHTO T358-22),[13] or embedded electrodes (**Fig. 1**). Measuring electrical resistivity is a nondestructive test, which means it can be repeated over time to gauge property development. While the sample does need time to cure and condition, the resistivity testing itself is relatively rapid and should therefore have lower costs than other methods.

Several recent efforts have been made to quantify the accuracy of resistivity testing. For example, a verification cylinder (**Fig. 2**) was created using resistors and capacitors that were capable of simulating concrete with a high and low performance according to

Table 1. Single-operator and multilaboratory coefficients of variation for various conditioning methods

Testing description	Testing standard	Conditioning method		
		Simulated pore solution	Sealed	Lime solution
Single operator	AASHTO T358: Surface resistivity[13]	6.3*	3.8*	5.8
	AASHTO T402: Bulk resistivity[12]	3.3	3.4	2.2*
Multilaboratory	AASHTO T358: Surface resistivity[13]	14.1*	11.0*	10.9
	AASHTO T402: Bulk resistivity[12]	13.0	11.3	9.5*

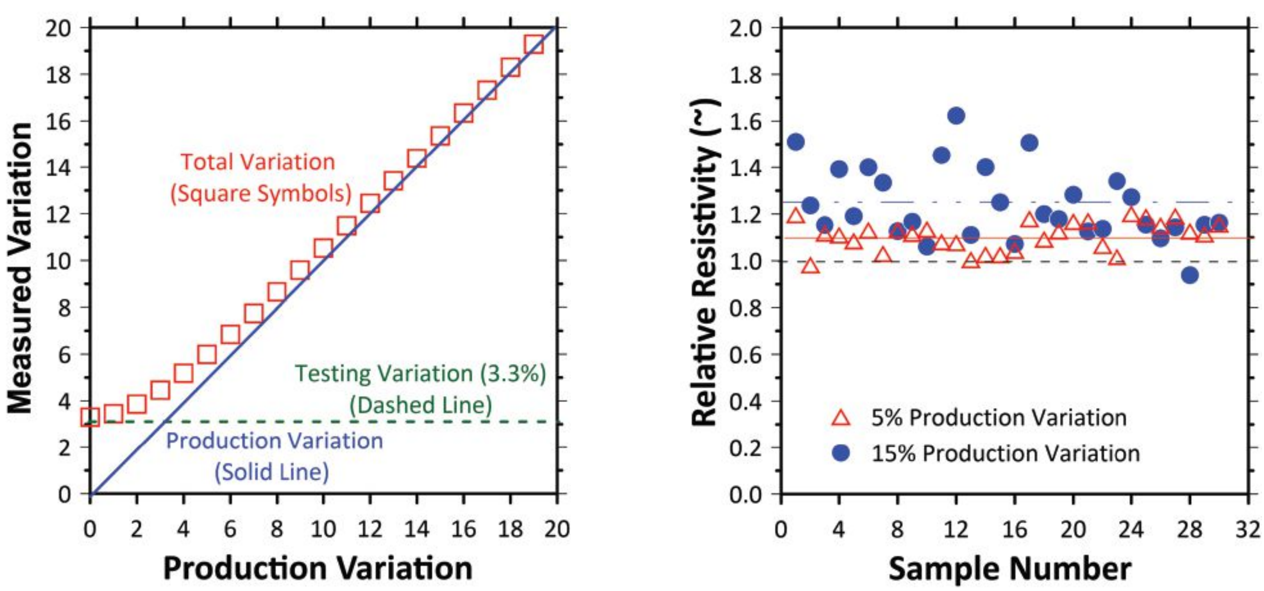
*Conditioning procedure not specified by AASHTO standard.

ASTM C1202[4] (RCPT of approximately 100 to 1000 C and more than 4000 C, respectively).[14] The verification device has two uses. First, it can be used for training new users and evaluating their ability to perform the test correctly. Second, it can be used to evaluate the bias (a measure of how far the measured value is from a true or known value) of various commercial testing devices. The results have a bias of 2.4% or less. **Table 1** provides the measured single-operator and multilaboratory coefficients of variation for the testing.[14] The conditioning method alters the ionic strength of the pore solution in the concrete, and it is important to know the ionic strength as it can be used along with the resistivity to determine the formation factor,[15] a fundamental measure of the pore structure that can be determined with the measured resistivity and information about the pore solution.

Single-operator precision testing is performed to quantify the acceptable variability when two tests are performed by the same operator. These data can be very useful for quality-control operations as they help establish the level of variability that can be expected from the test before the variability of the material processing is considered. Variations equal to or less than the single-operator variation are expected, and no changes in process should be needed. Table 1 shows the single-operator variations for the bulk and surface tests for three sample conditions. The total variation σ_{Total} of a measured sample collected during a construction project is the square root of the sum of the squares of the intrinsic material variability s_M, the sampling variability s_S, the testing variability s_T, and the production variability s_P. The the precision reported by the testing standard accounts for the first three sources of variability, whereas the production variability is related to how precisely the contractor can control the concrete constituent materials, mixing process, and placement. **Figure 3** illustrates the relationship between the measured variation (on the y axis) and the production variation (on the x axis). To achieve the target resistivity for a material with 95% confidence considering no production variation, the material should be designed with a mean that is 1.055 times the target value ($1.65 \times \sigma_{Total}$). Similarly, if a material has a production variation of 5%, 10%, 15%, or 20%, the mean value should be designed such that it is 1.10, 1.16, 1.25, or 1.30 times the target value, respectively.

The multilaboratory testing represents the acceptable variability when two tests are performed by different operators with different equipment (both the testing device and, more importantly, the curing and conditioning methods). This type of testing would be used to compare two different laboratories—for example, the producer performing quality-control and the owner performing quality-assurance testing, assuming these tests are done independently. The variation in testing devices is relatively low (generally, a coefficient of variation of less than 2%);

Figure 3. An illustration of the role of testing, production, and total variation, and how production variation and testing variation can affect the relative resistivity design target. Figure: Oregon State University.



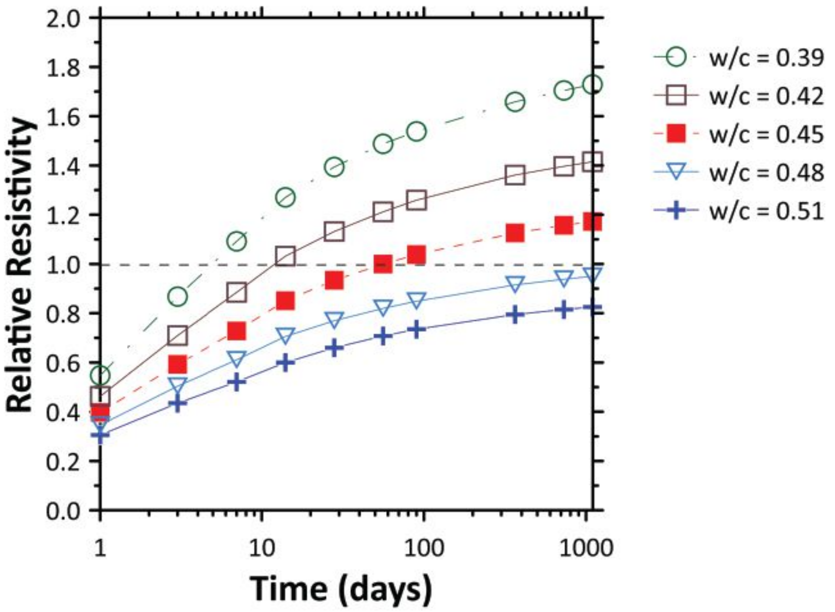


Figure 4. Predicted relative resistivity development for concretes with varying water-cement ratios. Figure: Oregon State University.

Table 1 shows the conditioning of samples and inherent material variation.

One benefit of using resistivity is the ability to track the development as a function of time. **Figure 4** estimates the relative resistivity development over time using thermodynamically based theoretical calculations for concretes with various *w/c*.[16–20] Two things become evident. First, the concretes with lower *w/c* have a higher resistivity. Second, and maybe more subtle, when specific resistivity values are required to meet a specification, they can be monitored over time and "deemed to satisfy" before a specific age. This monitoring also has the potential to be used as an early indication of long-term compliance.

While there are many benefits of resistivity testing, new users of the test should be aware that—unlike more classical tests such as strength—it may be impacted by testing temperature, sample conditioning, steel fibers, certain corrosion inhibitors, and degree of saturation.[10,21–24]

In summary, the electrical resistivity of concrete can be measured easily and provides useful information for quality control and quality assurance in concrete materials. Resistivity is a rapid, relatively low-cost, nondestructive test method to assess resistance to fluid and ion transport. This article outlines aspects of testing variation and indicates how they could be used for quality control. Furthermore, resistivity can be extended to service-life predictions, which can be beneficial in quantifying the long-term performance of concrete materials.[25]

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