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VARIABILITY ANALYSIS OF THE BULK RESISTIVITY MEASURED USING CONCRETE CYLINDERS

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16. Abstract

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Many agencies are interested in using a rapid test method for measuring the electrical properties of concrete (i.e., the resistivity or conductivity) since the electrical properties can be related to fluid transport (e.g., ion diffusion). The advantage of electrical testing is that it is relatively easy to perform and the test method is relatively fast (less than a minute). Over the last century, many studies have investigated different approaches for measuring electrical properties. This paper describes the variability associated with measuring the bulk resistivity along the longitudinal axis of a cylinder after placing electrodes on either end. A multi-laboratory evaluation was performed using ten laboratories. Data from this evaluation provided variability data for twelve concrete mixtures at testing ages of 28, 56, and 91 days. Information on the variability is important in the development of precision and bias statements for standard test methods. In addition, this work discusses how the resistivity results obtained from this test can be correlated with surface resistivity measurements made using the Wenner probe. A linear agreement was noticed between the Wenner test and the measurement through the cylinder, but with a factor confirmed by previous research by Morris et al. (1996). Additionally, the effect of electrode resistance was discussed and for high resistivity concrete such as that used in much of the transportation infrastructure, this effect appears to be negligible; however, it can be accounted for easily.

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INTRODUCTION

Over the last century, tests have been proposed to measure the electrical properties of concrete [1–7]. These methods have an advantage of being relatively fast to perform and the principle behind these tests is relatively straightforward. While concrete is a composite consisting of a vapor phase (vapor filled porosity or "air"), a solid phase (aggregate and cementitious solids) and a fluid phase (the pore solution) the conductivity of each of these individual phases are very different. The conductivity of the solid and vapor phases are extremely low, approximated as 10^9 and 10^{15} Ohm-m respectively, while the conductivity of the liquid phase is several orders of magnitude higher, ranging from 1 to 5×10^{-2}Ohm-m [8,9].

As such, it can be assumed that the majority of conduction occurs through the pore fluid. A number of composite models have been developed where this concept is used [10–13]. Two of the more popular equations that are used in the cement and concrete literature are Archie's expression and the modified parallel expression [11,14]. While several documents have reviewed these methods previously, the goal of this section is to describe that the overall resistivity is dependent on three factors (the resistivity of the fluid in the pores, the degree of saturation of the concrete, and the volume and connectivity of the pore network) as illustrated in Eq 1:

$$\rho_c = \rho_o \cdot F \cdot f(S) \qquad (1)$$

where ρ is the bulk resistivity, ρ_o represents the resistivity of the fluid phase, F is the formation factor which is function of the pore volume divided by a tortuosity coefficient, and $f(s)$ is a function that describes the degree of saturation which is taken as 1 for a saturated system. This implies that resistivity decreases with a higher water content (i.e., pore volume) and a more open pore network (i.e., a lower tortuosity coefficient). This expression can also be written in terms of electrical conductivity as it is simply the inverse of the electrical resistivity.

One of the more popular test methods that is currently performed based on electrical concepts is the Rapid Chloride Permeability Test or RCP test [15,16]. This test method involves placing a saturated concrete specimen, typically 102-mm diameter and 51-mm thick, between electrodes in different solutions and integrating the charge that is passed over a six hour testing period [15]. While this test has gained wide use, there are a few drawbacks that have been pointed out [17–19]. First this test is performed using high voltages and direct current which limit each sample to providing a single measurement at a single age. Second, saturating the specimen can take a relatively long preparation time. Third, the potential for heating effects due to the large voltage and possible modification of the microstructure [20,21]. There has been research regarding temperature correction for the RCP test [22,23], but for many RCP Proposed changes to this test have been proposed include extrapolating the charge passed after a test duration of 30-minutes and extrapolating to the 6-hour value [24], increasing the size of the reservoirs to reduce the heating effects [25], reducing the large voltages in the test [26], and using a single resistance reading measured at an early age, often 1-minute or 5-minutes [18,19].

Alternative testing methods have been proposed that require little to no sample preparation or enable the sample to be tested at different ages. One rapid test for electrical resistivity of concrete is the Wenner probe. As with any test, there are certain considerations that can impact the results. For example, the probe spacing, geometry of the sample, aggregate size and surface moisture conditions can all influence the measured electrical response [27]. Since the moisture conditions at the surface of the test specimens are quite important, care should be taken to protect against drying or using on surface treated concretes [28–30]. Additionally, some work has suggested the need for an additional non-linear geometry factor for this method that occurs from the constricted geometry, such as that of a standard test cylinder [27]. Further, when this method is used on real structures the location and proximity of the rebar needs to be considered [31,32].

Several of these concerns can be addressed if a standard testing protocol is adopted. A draft test method has been developed to use a four-probe Wenner configuration on a 102 mm × 205 mm cylinder test setups monitoring of temperature can be difficult or is frequently not done with probe spacing of 38.1 mm [33]. This surface resistivity (SR) test method places the probes directly on the surface of the test specimen. This test method has recently been accepted for use by the Louisiana Department of Transportation and by the Florida Department of Transportation on select projects and preliminary work has been done to expand its use for quality control [28,34]. Work has also been done to correlate RCP testing and diffusion testing with SR [28,35,36]. This method has a distinct advantage in that it is rapid to perform and easy to perform on the surface of a cylinder.

The resistance of a concrete cylinder can alternatively be evaluated by using plate electrodes that can be placed on the end of the sample [32,37]. The resistance value obtained can be normalized by specimen geometry, simply the ratio of sample cross-sectional area to length, to obtain the sample resistivity, termed the bulk resistivity (BR). For this test, good electrical contact must be ensured between the plate electrodes and the test specimen [27,37]. While this can be assisted through the use of a conductive medium, the surface finish of the cylinder ends should be flat. Some work has previously been performed on evaluating the contact pressure between the plate and the specimen [37]. Like other electrical tests this method is subject to the influence of specimen moisture content and temperature. This test however has the distinct advantage of rapid testing and a simple geometry factor. To the best of the authors' knowledge, a multi-laboratory evaluation of variability has not been performed on this geometry though some studies have reported exchanges of samples between two labs [37].

Three major factors that should be considered in any electrical resistivity testing are 1) the influence of geometry, 2) the influence of temperature, and 3) the influence of moisture. First, while the normalized bulk resistivity of concrete can be considered a material property, the tests that are performed provide a measure of electrical resistance. The resistance measurements need to be corrected for the geometry of the test. Geometry factors can be determined experimentally [8,38] or numerically [27]. Temperature is another important factor in the testing of concrete resistivity. This occurs as the primary conduction path is through the ionic pore solution; the increase of temperature increases the mobility of the ions decreasing the resistivity. There has been work that has investigated the possibility of a temperature correction for resistivity tests [6,39–43]. In this work the samples are all performed in laboratory conditions, as such the sample should be 23+/−2C. Lastly, the degree of saturation is a major component of the bulk resistivity of concrete. As such, knowledge of the moisture history and moisture content at testing are important considerations in the evaluation of resistivity data [44].

The main objectives of this evaluation are fourfold:

- First, it provides some background on electrical property measurements for concrete and provides some of the physical principles behind these tests.
- Second, it presents the results of an inter-laboratory evaluation of the variation in electrical bulk resistivity of concrete. This information can be used in the development of precision and bias statements
- Third, it demonstrates the relationship between surface resistance test methods (e.g. wenner) and measurements performed on a bulk cylindrical geometry.
- Fourth, it highlights important considerations in the development of testing standards and development of policies for the use of electrical methods as quality control/quality assurance tests.

EXPERIMENTAL DETAILS

Materials

A round robin test testing program was proposed in 2009 to evaluate the repeatability of the Wenner and bulk resistance tests on concrete cylinders. A series of twelve concrete mixtures were prepared at the laboratories who participated in this evaluation. The mixtures are structural/bridge deck concretes used by state departments of transportation from around the country. A final report detailing a parallel series of wenner and bulk resistivity tests conducted by AASTHO TIG group are available [45]. It should be noted that a wide range of cements, supplementary materials and aggregates were used in this investigation.

Sample Conditioning

The samples were demolded at an age of 48-hours and placed into a saturated lime-water bath kept at a constant room temperature until the age of testing (23+/ − 2C). At an age of 14-days, the respective laboratories removed the samples and wrapped them in paper towels soaked in saturated lime-water. The samples were then double-bagged and prepared to be shipped via two-day shipping to the other participating laboratories. The goal is to ensure the samples remain wet during testing.

After the samples were received by other testing laboratories, they were to be removed from the bag and placed into saturated lime water baths kept at room temperature (23+/− 2C). At ages of 28, 56, and 91-days, the samples were removed from saturated lime bath, the surface was wiped dry, and the samples were tested for SR and DR. After this testing the samples were placed back in the saturated lime water.

TABLE 1
Summary of mixture proportions used in this evaluation, (SSD)

Mixture No.	w/cm	Water kg/m^3	Cement kg/m^3	Fly Ash kg/m^3	Micron Fly Ash kg/m^3	Slag kg/m^3	Silica Fume kg/m^3	Meta-Kaolin kg/m^3	Coarse 1 kg/m^3	Aggregate 2 kg/m^3	Fine Aggregate kg/m^3
1	0.34	163	237	119	-	119	-	-	1059	-	717
2	0.40	144	285	71	-	-	-	-	282	854	824
3	0.39	199	392	119	-	-	-	-	785	-	724
4	0.35	158	279	178	-	-	-	-	940	-	793
5	0.40	164	308	103	-	-	-	-	909	-	879
6	0.37	145	390	-	-	-	-	-	1068	-	712
7	0.40	160	297	80	-	-	24	-	532	528	686
8	0.39	131	251	84	-	-	-	-	555	-	1295
9	0.41	151	291	65	-	-	15	-	1032	-	697
10	0.30	151	297	153	44	-	-	-	1009	-	638
11	0.30	157	430	95	-	-	-	-	1033	-	577
12	0.35	156	402	-	-	-	-	44	1009	-	624

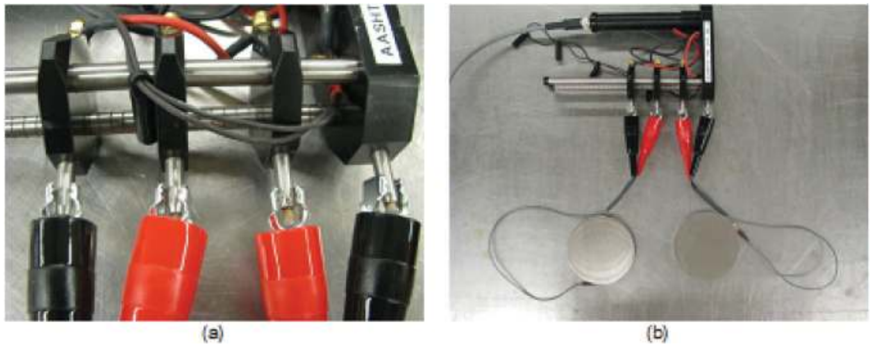


Fig. 1 Attach the alligator clips to the Wenner probe tips. a.) close up b.) at a distance

TESTING PROCEDURE

It should be noted that the test described herein (the plates placed on the end of the cylinder) was a part of a larger evaluation of variation conducted by the AASTHO TIG [45,46]. Not all of the laboratories chose to participate in this portion of the evaluation, so those laboratories have been excluded from the following data though to avoid confusion the original laboratory numbers were retained.

Equipment

The equipment involved in this test consisted of a CNS Farnell Mk II, U95 surface resistivity meter using an alternating current at 13 Hz, a set of 102-mm diameter stainless steel plate electrodes, and 16 gauge, two-conductor wire to connect the probe tips of the surface resistivity meter to the plate electrodes.

The cable was outfitted with alligator clips on one end to allow easy access to the probe tips of the resistivity meter. The other end of the cable was outfitted with a ring terminal to connect to the plate electrode. The plate electrode was drilled and tapped to allow easy and consistent attachment.

An important consideration is to ensure proper electrical contact between the cylinder and the plate electrodes [27,37]. For this evaluation, this was done using thin, lime-water saturated sponges.

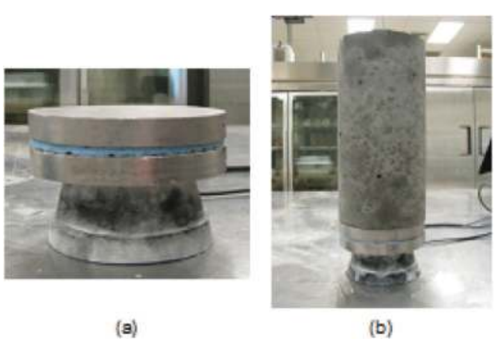


Fig. 2 Measuring the sponge resistance for a.) the top, and b.) the bottom sponges

Testing Procedure

The plate electrodes should be connected to the pins of the surface resistivity meter. The first two pins that generate the current and measure the potential were connected to one of the steel plate electrodes and likewise for the second set of pins, as shown in Fig.1.

The resistances of the top and bottom sponges were then measured, as shown in Fig.2. As resistance of the sponges is largely dependent on moisture content, a test cylinder was used to ensure the pressure on the sponge was consistent for the test of sponge resistance and the measurement of the test cylinder. This was to ensure approximately the same moisture content. The goal of this was to provide a correction for sponge resistance, as discussed below.

The concrete cylinder is then placed between the plate electrodes, with sponges being placed between the plates and the concrete cylinder, as shown in Fig. 3.

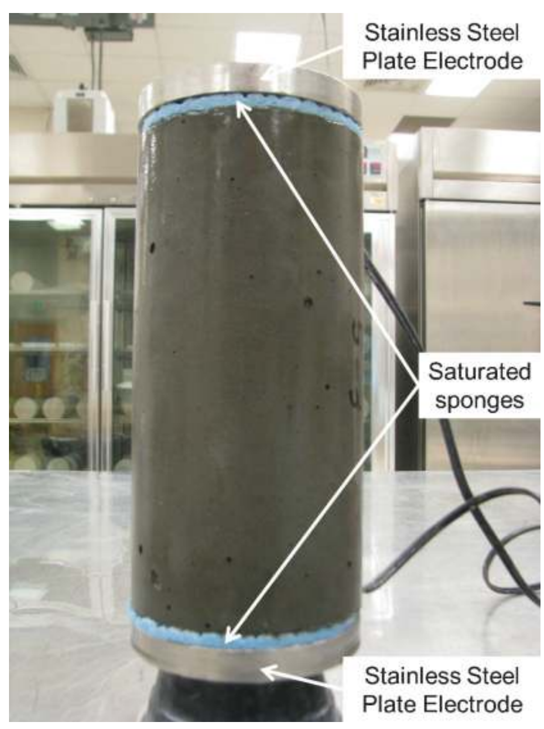


Fig. 3 Measuring the resistance of the system

Calculations

The resistances of the top and bottom of the top and bottom sponge are termed $R_{\text{top sponge}}$ and $R_{\text{bottom sponge}}$ respectively. The measured resistance of the system (two sponges and a specimen), as depicted in Fig. 3, was termed R_{measured}. The measured resistance was corrected for the resistance of the sponges by treating the system as resistors in series, as shown in Equation 2 [37]. It was noticed for the sponges used in this evaluation, resistance values in each lab tended to remain relatively constant. Thus, for sponges that show this constant resistance it is proposed they only be measured periodically and their resistances can be assumed.

$$R_{\text{cylinder}} = R_{\text{measured}} - R_{\text{top sponge}} - R_{\text{bottom sponge}} \quad (2)$$

The bulk resistivity, denoted ρ, can be determined by using Equation 2. Where the geometry factor, **K**, for current flow through the bulk material is given by Equation 3. This can be extended to other samples geometries through experimental testing [8].

$$\rho = \mathrm{K} \cdot R_{\text{cylinder}} \quad (3)$$

$$\mathrm{K} = \frac{\mathrm{A}}{\mathrm{L}} \quad (4)$$

where R_{cylinder} is the calculated resistance of the concrete test cylinder from Equation 1, **A** is the cross-sectional area, and **L** is the length of test specimen.

RESULTS AND DISCUSSION

Bulk Resistivity Data

The samples were tested at three ages: 28, 56, and 91-days. The average bulk resistivity (Avg.) and variance (Var.) of three test cylinders measured at each testing age for each mixture by each testing laboratory is presented below. Cells marked with n/a represent no data reported. The last row in the following tables represents the pooled statistics, calculated according to ASTM C802-09a [47].

Data measured at ages of 28-days is presented in Table 2. Mixtures 1 through 5 were not tested for 28-day BR as the equipment was in being distributed. Data measured at ages of 56-days is presented in Table 3. Mixture 1 was not tested for 56-day BR as the equipment had still not been received. Data measured at ages of 91-days is presented in Table 4.

The data presented in Tables 2 through 4 were analyzed according to ASTM C802-09a to determine the corresponding components of variance for the variability from within-laboratory and multi-laboratory. The within-laboratory variability is typically attributed to variability of the operator as well as variability inherent in the test equipment and in the samples being tested. It should be noted that using the approach taken for this round robin testing that variations between samples arising from sample preparation issues could contribute to this component of variability. This will be discussed later in this paper.

TABLE 2
Average BR and variance obtained at a testing age of 28-days

Laboratory		Mixture 1	2	3	4	5	6	7	8	9	10	11	12
1	Avg.	n/a	n/a	n/a	n/a	n/a	5.29	13.41	14.97	8.84	12.67	6.46	14.89
	Var.	n/a	n/a	n/a	n/a	n/a	0.03	0.15	1.28	0.16	0.06	0.03	0.82
2	Avg.	n/a	n/a	n/a	n/a	n/a	5.27	14.12	16.98	8.36	13.49	6.73	18.84
	Var.	n/a	n/a	n/a	n/a	n/a	0.01	0.21	0.18	0.02	0.30	0.64	0.61
3	Avg.	n/a	n/a	n/a	n/a	n/a	5.19	13.54	14.03	7.69	11.53	5.43	16.04
	Var.	n/a	n/a	n/a	n/a	n/a	0.03	0.12	0.24	0.14	0.17	0.05	1.71
5	Avg.	n/a	n/a	n/a	n/a	n/a	5.65	15.19	16.73	8.31	16.93	7.36	n/a
	Var.	n/a	n/a	n/a	n/a	n/a	0.05	0.10	0.47	0.13	0.16	0.10	n/a
6	Avg.	n/a	n/a	n/a	n/a	n/a	5.55	15.24	15.69	9.60	13.72	6.68	20.24
	Var.	n/a	n/a	n/a	n/a	n/a	0.10	0.17	0.09	0.08	0.43	0.05	0.01
7	Avg.	n/a	n/a	n/a	n/a	n/a	5.03	13.59	15.01	8.91	12.87	6.88	16.90
	Var.	n/a	n/a	n/a	n/a	n/a	0.04	0.12	0.16	0.01	0.14	0.07	0.07
8	Avg.	n/a	n/a	n/a	n/a	n/a	5.84	14.36	16.58	8.63	14.59	6.81	18.21
	Var.	n/a	n/a	n/a	n/a	n/a	0.03	0.36	0.14	0.10	0.45	0.13	0.15
9	Avg.	n/a	n/a	n/a	n/a	n/a	5.31	14.39	16.37	8.91	13.15	7.00	16.48
	Var.	n/a	n/a	n/a	n/a	n/a	0.00	0.01	0.11	0.05	0.40	0.04	0.84
10	Avg.	n/a	n/a	n/a	n/a	n/a	5.12	14.20	15.60	8.62	14.22	6.77	18.55
	Var.	n/a	n/a	n/a	n/a	n/a	0.00	0.05	0.02	0.39	0.13	0.01	0.12
12	Avg.	n/a	n/a	n/a	n/a	n/a	5.68	14.02	15.11	8.30	12.30	6.40	16.76
	Var.	n/a	n/a	n/a	n/a	n/a	0.01	0.20	0.04	0.21	0.26	0.13	0.11
All Labs	Mean	n/a	n/a	n/a	n/a	n/a	5.39	14.21	15.71	8.62	13.55	6.65	17.43
	Pooled Variance	n/a	n/a	n/a	n/a	n/a	0.03	0.15	0.27	0.13	0.25	0.13	0.49
	Variance	n/a	n/a	n/a	n/a	n/a	0.07	0.40	0.90	0.26	2.22	0.26	2.72

TABLE 3
Average BR and variance obtained at a testing age of 56-days

Laboratory		Mixture 1	2	3	4	5	6	7	8	9	10	11	12
1	Avg.	n/a	6.73	8.76	12.63	8.07	6.56	24.34	29.99	14.78	22.20	11.98	18.14
	Var.	n/a	0.07	0.08	0.18	0.01	0.03	0.04	0.05	0.15	0.34	0.09	0.03
2	Avg.	n/a	8.64	9.10	12.05	10.83	7.22	24.52	27.25	13.14	22.53	12.69	20.12
	Var.	n/a	0.38	0.05	0.10	0.65	0.09	1.28	0.11	0.05	0.79	0.64	0.42
3	Avg.	n/a	6.18	7.81	12.26	7.71	5.81	23.13	21.61	12.17	17.26	n/a	17.71
	Var.	n/a	0.23	0.05	0.01	0.00	0.00	0.73	0.39	0.11	0.19	n/a	1.48
5	Avg.	n/a	7.98	9.26	11.41	7.26	7.08	24.10	29.12	14.92	22.48	10.91	n/a
	Var.	n/a	0.00	0.48	0.03	0.12	0.02	0.39	0.24	1.12	0.14	0.01	n/a
6	Avg.	n/a	7.70	9.16	12.89	9.99	6.70	n/a	25.02	n/a	19.62	10.09	21.49
	Var.	n/a	0.06	0.46	0.02	0.01	0.21	n/a	0.87	n/a	0.78	0.08	0.12
7	Avg.	n/a	8.38	8.55	12.34	8.33	6.57	24.20	27.18	16.50	21.37	12.16	19.88
	Var.	n/a	0.64	0.09	0.08	0.05	0.04	0.27	1.46	0.06	0.02	1.03	0.62
8	Avg.	n/a	7.18	9.27	13.64	9.31	6.72	25.89	31.29	14.38	24.98	12.55	20.85
	Var.	n/a	0.18	0.12	0.06	0.08	0.03	1.73	0.68	0.25	0.36	0.10	0.46
9	Avg.	n/a	n/a	9.20	13.50	8.59	6.52	26.09	30.28	15.13	23.23	13.43	20.27
	Var.	n/a	n/a	0.11	0.72	0.01	0.05	0.07	0.81	0.10	0.93	0.22	0.25
10	Avg.	n/a	7.98	8.92	14.85	7.94	6.26	26.58	26.03	14.20	22.24	11.22	21.46
	Var.	n/a	0.00	0.23	0.61	0.13	0.01	0.34	0.08	0.81	0.17	0.03	0.25
12	Avg.	n/a	6.10	8.34	11.94	7.90	6.52	22.21	23.65	13.06	18.67	9.95	15.99
	Var.	n/a	0.03	0.01	0.03	0.16	0.03	1.76	0.68	0.53	0.73	0.05	0.86
All Labs	Avg. Mean	n/a	7.43	8.84	12.75	8.59	6.59	24.56	27.14	14.25	21.46	11.66	19.55
	Avg. Variance	n/a	0.18	0.17	0.18	0.12	0.05	0.73	0.54	0.35	0.44	0.25	0.50
	Variance	n/a	0.86	0.23	1.02	1.25	0.15	2.02	9.74	1.70	5.29	1.44	3.52

TABLE 4
Average BR and variance obtained at a testing age of 91-days

Laboratory		Mixture 1	2	3	4	5	6	7	8	9	10	11	12
1	Avg.	10.24	8.07	12.14	18.71	11.36	7.58	38.05	42.08	19.44	34.98	17.90	18.80
	Var.	0.19	0.05	0.23	0.39	0.02	0.06	0.01	7.14	0.37	1.22	0.20	0.79
2	Avg.	12.16	10.43	15.12	18.83	16.81	8.31	32.40	39.19	17.58	29.78	16.17	24.58
	Var.	0.48	0.12	0.94	0.77	0.62	0.04	2.72	0.25	0.04	1.25	0.89	1.08
3	Avg.	10.43	7.85	10.61	16.58	9.46	6.65	28.87	31.78	14.63	22.71	13.10	17.18
	Var.	0.16	0.43	0.68	0.07	0.19	0.26	2.12	2.63	0.32	0.21	0.79	0.36
5	Avg.	11.01	8.36	12.12	16.21	10.20	8.48	33.45	37.14	20.19	28.66	15.45	n/a
	Var.	0.20	0.02	0.47	0.05	0.16	0.02	0.50	1.07	2.72	0.27	0.29	n/a
6	Avg.	13.91	10.11	14.34	23.58	n/a	7.65	30.97	30.81	15.60	29.92	15.80	20.96
	Var.	0.00	0.03	1.04	0.09	n/a	0.40	0.98	0.05	0.35	0.89	0.06	0.01
7	Avg.	10.67	10.05	14.11	19.27	12.58	7.94	35.83	40.06	20.81	29.55	17.18	21.03
	Var.	0.15	0.44	0.83	0.04	0.08	0.03	0.70	2.41	0.05	0.10	0.03	0.48
8	Avg.	12.22	8.92	13.25	20.47	13.29	7.67	38.06	45.59	19.19	35.36	18.49	20.29
	Var.	0.02	0.23	0.18	0.23	0.11	0.05	4.03	1.94	0.43	1.04	0.18	0.51
9	Avg.	11.16	10.09	14.35	19.54	12.06	8.60	37.74	43.37	n/a	34.48	22.41	19.55
	Var.	0.00	0.59	0.05	2.77	0.10	0.42	0.02	9.91	n/a	3.77	4.91	0.79
10	Avg.	12.39	9.75	13.71	22.44	12.65	6.74	37.54	38.41	18.26	30.51	16.50	21.15
	Var.	0.07	0.80	0.34	2.00	1.42	0.00	0.24	0.08	1.21	0.46	0.14	0.23
12	Avg.	10.07	7.82	11.12	15.96	10.40	7.26	31.21	33.11	14.93	22.67	12.69	18.01
	Var.	0.23	0.02	0.00	0.04	0.15	0.04	3.08	1.92	0.52	0.78	0.01	0.02
All Labs	Avg. Mean	11.43	9.15	13.09	19.16	12.09	7.69	34.41	38.15	17.85	29.86	16.57	20.17
	Avg. Variance	0.15	0.27	0.47	0.65	0.32	0.13	1.44	2.74	0.67	1.00	0.75	0.47
	Variance	1.48	1.10	2.29	6.45	4.77	0.45	11.91	24.83	5.35	20.28	7.67	4.70

TABLE 5
Average within-laboratory coefficient of variation

Testing Age	within-laboratory coefficient of variation
28-days	3.34 %
56-days	3.87 %
91-days	4.36 %

Within-laboratory Variability

The operator variability, variability of specimens, and the inherent variability in the mixture are all associated together into the within laboratory variability. This was computed using the average within-laboratory coefficient of variation, COV, presented in Table 5 [47]. Previous work evaluating the development of an automated resistivity testing system has reported similar within-laboratory coefficient of variation around 3 % to 4 % for samples older than 24-hours. [48]. It should be noted that the variation increases over time. It is believed that this may be due to slight variations in curing conditions which may have occurred at each lab which could amplify differences overtime.

Multi-laboratory Variability

The multi-laboratory variability can be described by the average coefficient of variation computer from the multi-laboratory component of variance [47]. The average values of multi-laboratory coefficient of variation are shown Table 6. It should be noted that the variation increases over time. Again, slight variations in curing conditions which may have occurred at each lab which could amplify differences overtime.

Precision Statements

Precision estimates were calculated [49]. For this experiment, the fundamental statistic was determined to be the COV, represented as 1s% in ASTM C670-10. Therefore, the calculated precision indices will correspond to d2s% described in ASTM C670-10, determined by multiplying the average coefficient of variation by the factor $2\sqrt{2}$ [49]. This index represents the maximum difference between two individual test results, expressed as a percentage of their average. The precision indices for different testing ages are shown in Table 7.

The maximum precision index for the within-laboratory and multi-laboratory variability will be used to form the precision statements, which corresponds to the testing age at 91-days.

TABLE 6
Average multi-laboratory coefficient of variation

Testing Age	multi-laboratory coefficient of variation
28-days	7.75 %
56-days	9.83 %
91-days	13.22 %

TABLE 7
Precision indices for direct resistivity

Testing Age	within-laboratory	multi-laboratory
28-days	9.44	21.93
56-days	10.94	27.82
91-days	12.34	37.38

The maximum pooled single-operator coefficient of variation was found to be 4.36 %. Therefore, the results of two properly conducted tests by the same operator on the same concrete material at the same age are not expected to differ by more than 12.34 % of their average. The maximum pooled multi-laboratory coefficient of variation was found to be 13.22 %. Therefore, the results of two properly conducted tests by different laboratories on the same concrete material at the same age are not expected to differ by more than 37.38 % of their average.

These precision statements can be compared with the precision statements obtained for other test methods [15,45]. To remain consistent, the SR data from Jackson (2011) was analyzed according to the same procedure described in this paper [45]. Two tests done by the same operator on material from the same concrete mixture should not differ, from their average, by more than 42 % for the RCP test, 13.28 % for the surface resistivity test (each test consisting of 8 average measurements), and 12.34 % for the bulk resistivity test (each measurement consisting of 1 measurement). For tests conducted in separate laboratories, results should not differ, from their average, by more than 51 % for the RCP test, 34.55 % for the surface resistivity test, and 37.38 % for the bulk resistivity test. It should be noted that since the surface resistivity test is sensitive to the specific location that measurements are taken, an average of eight measurements for each sample, which contributes to smaller variability in the pooled statistics. However, this takes more time to perform the test. Conversely, the bulk measurement described herein is a single measurement.

Correlation with Other Electrical Tests Methods

Surface resistivity measurements were conducted as a part of this evaluation [45]. Fig. 4 compares the measured SR and the calculated BR.

A linear correlation was noticed, with an R^2 = 0.9986, with SR measurements tending to be 1.86 times higher than BR. This large data of experimental results support previous work using finite element that showed additional geometry factors must be used to account for test geometry, such as probe spacing, cylinder length, and cylinder diameter [27]. The factor of 1.86 is in good agreement with the geometric correction proposed by Morris et al. (1995) for a cylinder with a length of 205 mm, diameter of 102 mm, probe spacing of 38.1 mm and a MSA of 19 mm, which was approximately 1.9.

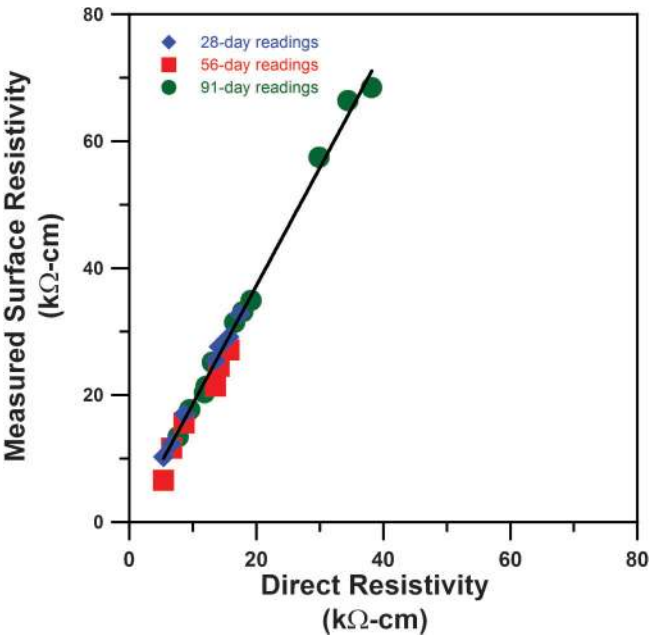


Fig. 4 Correlation of measured SR and BR of samples from differing ages. Each data point represents the average of three samples

As the RCP test is a widely used test for mixture characterization, Table 8 has been prepared to relate concrete resistivity to values obtained from an RCP test and surface resistivity. Previous empirical studies have also shown that RCP values can be related to concrete resistivity, termed Berke empirical, and RCP values to apparent surface resistivity, termed Paredes empirical [28,36].

The concrete resistivity is used to determine the resistance of a standard specimen for RCP (i.e., a 102 mm × 51 mm disc). Ohm's law is used to relate the specimen resistivity to the current assuming a voltage of 60 V. The current is integrated over a time of six hours to determine total charge [15]. This is a direct computation that does not consider temperature effects or possible damage previously discussed. The values for direct resistivity or apparent surface resistivity can then be ranked as classified by the RCP test method [15].

Effects of Electrode Resistance

Previous work has shown that electrode resistance (and other factors to insure connectivity between the electrode and sample) may influence the results as discussed in Equation 2.

The major contributor to electrode resistance is poor contact between the plate electrode and the surface of the test cylinder. Some work has suggested the possibility of using flexible electrodes [27]. An alternative solution is to use an aid that allows for good electrical contact. In the laboratory, this can be accomplished through the use of an electrically conductive jelly [50,51]. The alternative is to use another soft, conductive medium. Popular solutions have included the use of saturated sponges, chamois cloth, and paper towels [21,37].

An important issue becomes the associated resistance of the sponges. Previously, this associated resistance can be treated as a series of resistors in parallel with the test cylinder, which produces the correction shown and described by Eq2.

The sponge resistance is largely dependent on the moisture content of the sponges and the conductivity of the solution in which they are saturated. For this evaluation, the solution was saturated lime water, which was also used as the storage solution for the test cylinders. Furthermore, to ensure proper moisture content, the contact pressure for the sponge was kept constant between the sponge resistivity test and the cylinder test, as shown in Figs 2 and 3.

While this correction provides the truest value for bulk resistivity, the results of this evaluation show that this correction might not always be very large. For the sponges used in this evaluation, the resistances of the two sponges were much less than the resistance of the cylinder. Fig 5a shows the measured resistance (i.e., sample, sponges and electrodes) as a function of the cylinder resistance (i.e., the sample alone), as defined in Eq 2.The best fit line, given by Eq 5a with an R^2 of 0.9997, shows less than an average 2 % difference between the measured resistance and the cylinder resistance.

Additionally, the ratio of the measured resistance to the actual cylinder resistance, as defined in the

TABLE 8
Relationships between values provided by different electrical test methods

ASTM C1202 Classification(1)	Charge Passed (Coulombs)(1)	Direct Resistivity (kOhm-cm)(2)	Berke Empirical (kOhm-cm)	Paredes Empirical (kOhm-cm)(3)	Apparent Surface Resistivity (102mm × 205mm) (kOhm-cm)(4)
High	>4,000	< 5.2	< 4.9	< 6.5	< 9.7
Moderate	2,000 – 4,000	5.2 – 10.4	4.9 – 8.76	6.5 – 11.3	9.7 – 19.3
Low	1,000 – 2,000	10.4 – 20.8	8.8 – 15.6	11.3 – 19.9	19.3 – 38.6
Very Low	100 – 1,000	20.8 – 207	15.6 – 105.9	19.9 – 136.6	38.6 – 386
Negligible	< 100	> 207	> 105.9	> 136.6	> 386

(1)from ASTM C1202-10 [15]
(2)calculated using Ohm's law and geometry
(3)corrected for geometry from Kessler, et al. [28]
(4)bulk resistivity multiplied by geometry factor

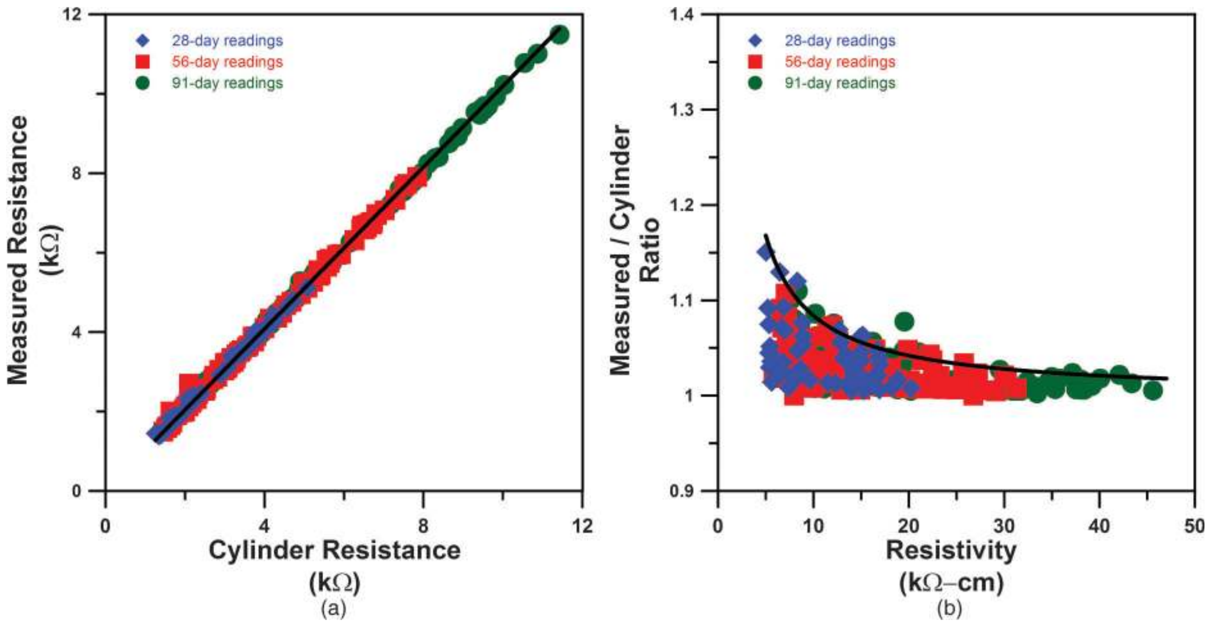


Fig. 5 Influence of electrode resistance on a.) the measured resistance (sample and electrodes) as a function of the cylinder (sample) resistance and b.) the ratio of measured resistance (sample and electrodes) and cylinder (sample) resistance as a function of concrete resistivity

preceding paragraph, can be shown against the concrete resistivity, depicted in Fig 5b. This ratio represents the correction from cylinder resistance. Fig 5b shows an upper bound of this ratio, given by Eq 5b. We can see for lower concrete resistivities, the ratio can be significant. However, for better concrete (i.e., higher resistivity concrete), this ratio approaches 1.

$$\text{Measured Resistance} = 1.019 \times \text{Cylinder Resistance} \quad (5a)$$

$$\frac{\text{Measured Resistance}}{\text{Cylinder Resistance}} = 1.0 + 0.84 \times \frac{1}{\text{concrete resistivity}} \quad (5b)$$

SUMMARY AND CONCLUSIONS

This paper reports results from a multi-laboratory investigation of the variability associated with testing the electrical bulk resistivity of concrete cylinders by placing plate electrodes on the ends of the cylinder. An analysis of the data is presented. The following observations can be made regarding the variability of the resistivity test method. It should be noted that the samples used in this evaluation were conditioned by storing the samples in lime saturated water between test measurements. First, resistivity testing is a rapid test that drastically reduces the amount of time a technician needs to spend conditioning the sample and conducting the test. Therefore, this test is well suited for quality control testing. Second, resistivity testing can be considered a non-destructive test. This means that for each mixture being evaluated using resistivity, only a small number of samples need be prepared and these samples can be measured at several different ages. This can be contrasted with other destructive electrical tests that require a larger series of samples for proper mixture evaluation. In fact, this testing can be performed on cylindrical samples before they are tested for compressive or splitting tensile strength. Third, the operator and multi-laboratory precision of this test method have been quantified using data from the average COV obtained from an inter-laboratory evaluation consisting of ten laboratories and twelve differing mixtures. For the direct resistivity test method, the within-laboratory COV is 4.36 % and the multi-laboratory 13.22 %. Fourth, specimen geometry can greatly influence the results of an electrical test. This often requires the use of a geometry correction factor. For the direct resistivity test, this geometry factor is simply the ratio of sample area to sample length. Finally, the effects of electrode resistance were addressed using a series model. While previous work described corrections for end plate resistance, the variability data from this investigation shows that for the materials used in this evaluation, the correction that is needed is quite small. It is suggested that a standard resistivity test be developed that could enable samples to be tested using a variety of sample geometries including 1) the wenner probe geometry, 2) the direct bulk resistance described herein, and 3) alternative geometries provided the geometry factor can be quantified. These could enable all the different methods to be used to obtain the material property known as bulk resistivity.

APPENDIX

SUPPLEMENTAL TEST METHOD FOR MEASURING

DIRECT ELECTRICAL RESISTANCE WITH THE WENNER PROBE APPARATUS

1. SCOPE

This test method covers the determination of electrical resistivity or conductivity by measuring the direct electrical resistance of the cylindrical concrete specimen.

2. REFERENCED DOCUMENTS

AASHTO Surface Resistivity Draft

3. SUMMARY OF TEST METHOD

This test method consists of applying a potential difference to the cylindrical specimen, thereby generating a current flow through the cylinder. The potential difference and resulting current can be used to determine the electrical resistance. Resistance is normalized by specimen geometry to obtain resistivity. Furthermore, the theory of resistors in series is used to account for the resistance of the sponges.

4. SIGNIFICANCE AND USE

Direct resistivity is related to water content, pore fluid resistivity, and pore tortuosity which is a direct interest in the study of transport properties.

5. APPARATUS

5.1 Wenner Probe Array

This test will be conducted with the device used in the measurement of surface resistivity. This is shown in Figure A1.

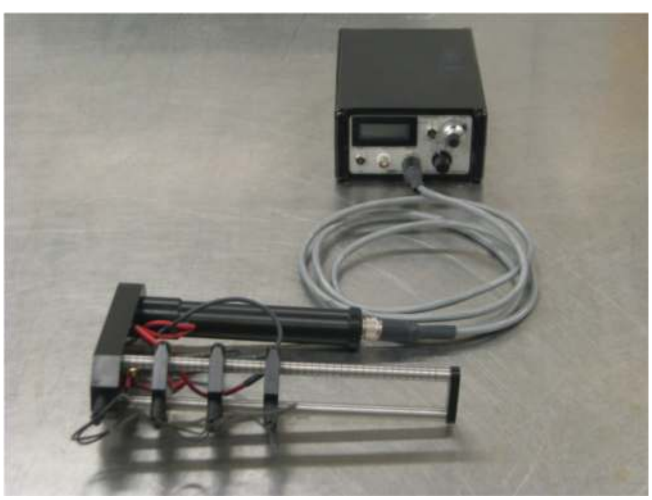


Fig. A1 Wenner Probe Array

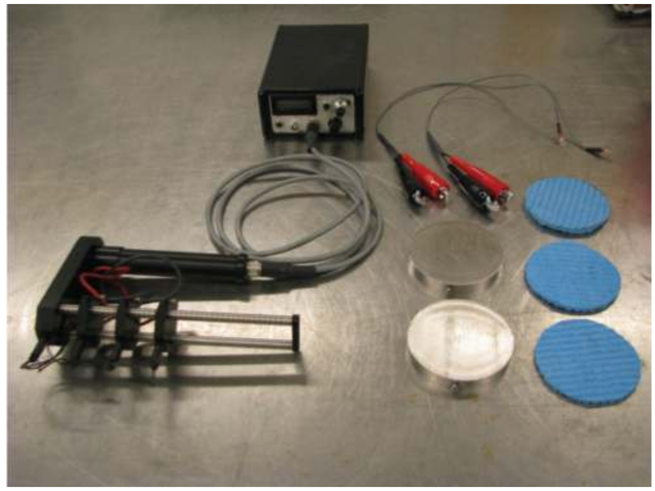


Fig. A2 Summary of provided equipment

5.2 Sponges

Sponges are used to improve the electrical connection between the plates and the sample. Sponges should be as close as possible to the specimen diameter, to ensure proper coverage and good contact. Also, they should be thin as possible. (See Figure A2.)

5.3 Stainless-Steel Plates

These plates act as electrodes when connected to the probe tips. The goal is to apply a potential difference over the sample cross-section. (See Figure A2.)

5.4 Cables

Each cable contains two, 22-gauge wires. The end of cable with the single ring terminal is attached to the stainless-steel plate with the screws. The other end of the cable is connected via alligator clip to the Wenner Probe device. (See Figure A2.)

6. TEST SPECIMENS

The test specimens that will be tested in this program consist of the three, 4-inch diameter, 8-inch length cylinders prepared by their respective agencies. Samples should be cured as prescribed by the Surface Resistivity study guidelines. As with the current test method, this supplemental method calls for the sample to be free of surface moisture.

7. PROCEDURE

7.1 Assemble Test Kit

The ring terminal end of the cable should be attached to the plate using the included screws. To attach the cable fully remove the screw, pass through the ring terminal, and reattach to plate. Make sure the connection is tight to ensure good electrical conductivity. Repeat this for the second plate and cable. This is shown in Figure A3.

Attach the alligator clip end of the cables to the Wenner probe as shown in Figure A4. Ensure that the top plate is connected to the

Fig. A3 Attach the cables to the plate

first two probe tips at one side and the bottom plate is connected to the first two probe tips from the other side.
Place the bottom plate on a non-conductive material, such as a piece of rubber, to ensure no extraneous interactions. Attach the Wenner Probe to the RM using the socket on the front of the device. Saturate the sponges in the lime water in which the cylinders are stored.

7.2 Using the Wenner Probe to Measure Resistance

The RM uses the probe tip spacing to calculate and display surface resistivity. Surface resistivity is denoted as "ρ" on the function switch and is the default position of the function switch.

By moving and holding the function switch up to the "Rc/10" position, the value of resistance is measured. Note that the function switch must be held in the "Rc/10" position for resistance measurements. The value displayed, while the function switch is in the "Rc/10" position, should be multiplied by ten to have units of kΩ.

7.3 Resistance of the Top Sponge

The stresses on the top sponge include just the weight of the top plate. This step simulates that pressure. Remove one of the sponges from the solution, let it drip water but do not squeeze it, then place it on the bottom plate. Lightly place the top plate on

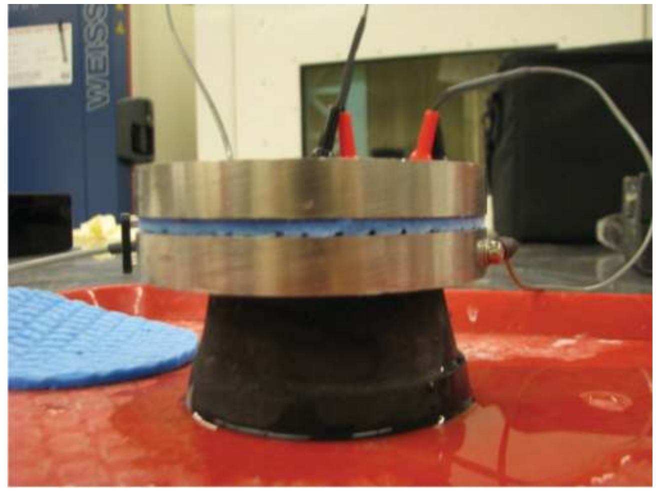


Fig. A5 Measure the resistance of the top sponge

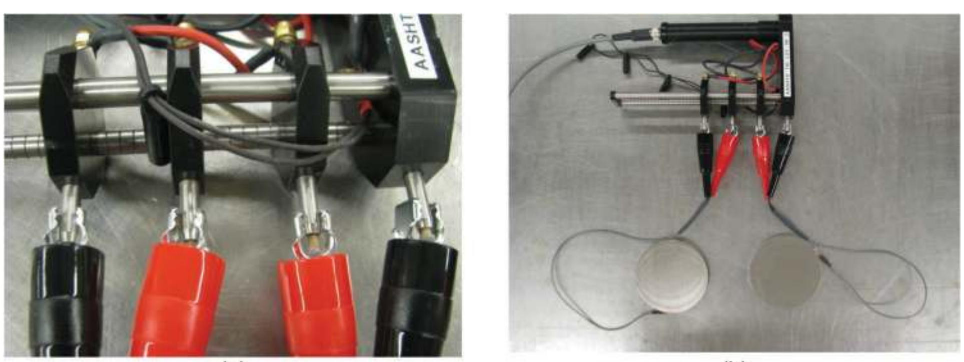
the top of the sponge. (See Figure A5) Tap dry any water released by the sponge, as this may cause incorrect resistance values.

The preparation of the top sponge described in this section helps to ensure excess water is not released during the measurement of the sponge-cylinder-sponge system described in 7.5
Measure the resistance of the top sponge by holding the function switch to "Rc/10". As discussed in 7.2, report and record the value on the display multiplied by ten.
Remove the top plate, light set the sponge aside on dry, non-absorbent surface. (i.e., not a paper towel)

7.4 Resistance of the Bottom Sponge

The stresses on the bottom sponge include the weight of the top plate and the weight of the cylinder. This step simulates that pressure. Remove the second sponge from the solution, let it drip water but do not squeeze it, then place it on the bottom plate. Lightly place the top plate on the top of the sponge. On top of the top plate, lightly place the test cylinder (See Figure A6). Tap dry the water released by the sponge, as this may cause incorrect resistance values.

The preparation of the bottom sponge described in this section helps to ensure no excess water is released during the measurement of the sponge-cylinder-sponge system described in 7.5
Measure the resistance of the bottom sponge by holding the function switch to "Rc/10". As discussed in 7.2, report and record the value on the display multiplied by ten.
Remove the cylinder and the top plate.



(a) (b)

Fig. A4 Attach the alligator clips to the Wenner probe tips. a.) close up b.) at a distance

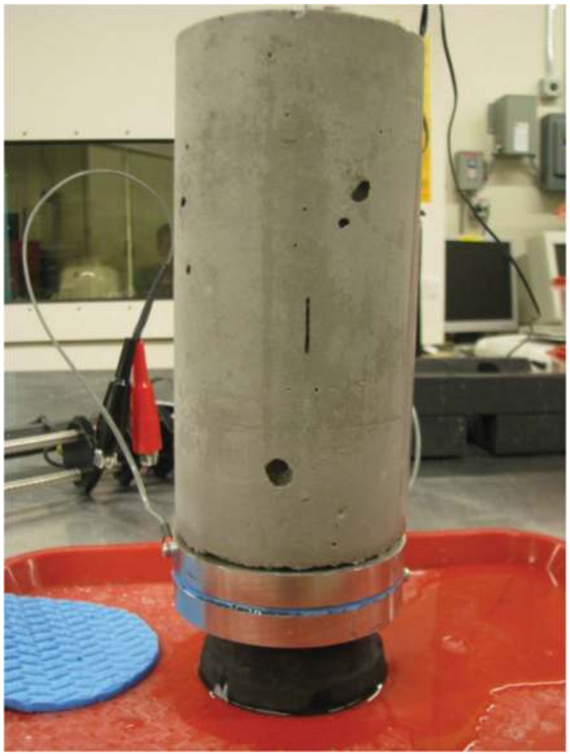


Fig. A6 Measure the resistance of the bottom sponge

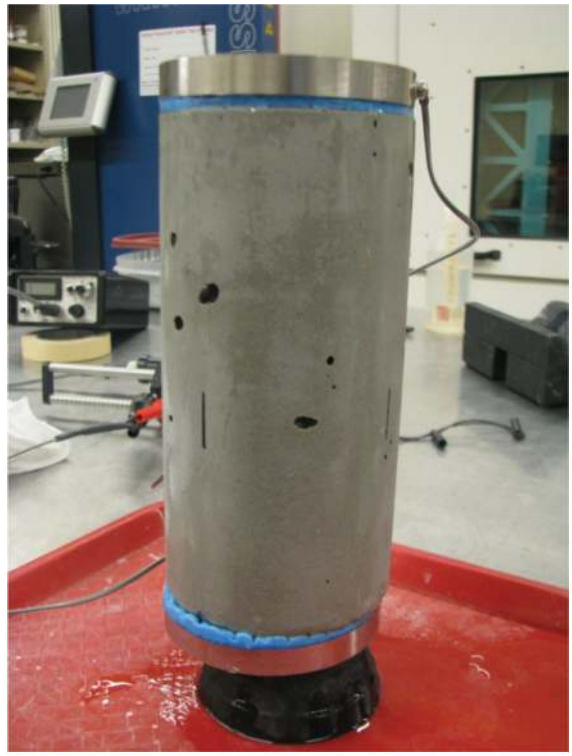


Fig. A7 Measure the resistance of the cylinder

7.5 Bulk Resistance of the Sponge – Cylinder – Sponge System

Place the cylinder on top of the sponge currently on the bottom plate. Place the sponge from 7.2 on the top of cylinder. Lightly place the top plate on the top sponge. The system setup can be seen in Figure A7.

Measure the resistance of the sponge-cylinder-sponge system by holding the function switch to "Rc/10". As discussed in 7.2, report and record the value on the display multiplied by ten.

7.6 Repeat

Prepare the sponges as described in sections 7.3 and 7.4 for each cylinder measured. Measurement of their resistances is not needed. This is namely the first paragraph in each section. This step helps to ensure that the sponges are in the same condition and have the same resistance as measured in steps 7.3 and 7.4.

Measure the resistance of the system as described in section 7.5 for each of the cylinders being tested

8. CALCULATION

8.1 Bulk Resistance of the Concrete Cylinder

The Sponge – Cylinder – Sponge system measured in step 7 can be modeled as a set of resistors in series. For resistors in series, the total resistance is the sum of each resistance. As such, the bulk resistance of the cylinder can be found by subtracting the sponges' resistance from that of the system.

$$R_b = R_{system} - R_{bot_{tom}} - R_{top} \quad \text{(Eq.1)}$$

8.2 Resistivity

The procedure prescribed in section 7 will provide the bulk resistance of the system, R_{system}, and the bulk resistance of the concrete cylinder, R_b, will determined following section 8.1. The value obtained in 8.1 will be normalized by specimen geometry to provide resistivity:

$$\rho = \frac{R_b \cdot A}{1}. \quad \text{(Eq.2)}$$

ρ is the resistivity (Ω.cm),$R_b$is the calculated bulk resistance (Ω). In this experiment, cylindrical samples were used, therefore, A would be the surface area of the sample (cm^2) and L is the length of the cylinder (cm).

The nominal geometries for this round of tests are provided in Table 1; however, these might change depending on the specimens.

9. REPORT

In addition to the reporting requirements of the Surface Resistivity, the measured resistances of: the top and bottom sponges and the sponge – cylinder – sponge system should be reported.

TABLE A1
Nominal specimen geometries

Area (cm^2)	81.07
Length (cm)	20.32

Fig. 1 The resolution switch (noted in yellow) can be moved to increase/decrease the resolution of the display

SUPPLEMENTAL NOTES

CHANGING THE RESOLUTION

The resolution can be changed by moving the range switch. This does not affect the calibration, but it will affect the resolution of the display.

For the bulk resistance measurements that we have done, to get the full resolution the range switch must be turned down to 1. It is important that this be returned to its standard operating position when measuring surface resistivities.
The range switch is noted in Figure 1 with a large yellow circle. Smaller numbers on the range switch will provide a higher resolution.
Take care not move the spacing dial, as that will affect the surface resistivity measurements.

ENSURING GOOD ALIGATOR CLIP CONNECTION

The wooden dowels on the probe tips have a tendency to dry, which can cause their electrical resistance to fluctuate. For this reason, please make sure that the alligator clips are securely fastened to the metal probe tips, as shown in Figure 2.

Fig. 2 Ensure the alligator clips are securely fastened to the metals tips

LOW BATTERY BEHAVIOR

We have noticed that when the low-battery indicator light (a battery shaped icon) is shown on the display, readings can be inconsistent. Because of this, it is recommended that the batteries be replaced when this light is shown.

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