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Relating the Electrical Resistance of Fresh Concrete to Mixture Proportions

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ABSTRACT

Characterization of fresh concrete is critical for assuring the quality of the United States' constructed infrastructure. While fresh concrete arriving at a job site in a ready-mixed concrete truck is typically characterized by measuring temperature, slump, unit weight, and air content, here the measurement of the electrical resistance of a freshly cast cylinder of concrete is investigated as a means of assessing mixture proportions, specifically cement and water contents. Both cement and water contents influence the measured electrical resistance of a sample of fresh concrete: the cement by producing ions (chiefly potassium, sodium, and hydroxide) that are the main source of electrical conduction and the water by providing the main conductive pathways through which the current travels. Relating the measured electrical resistance to attributes of the mixture proportions, such as water-cement ratio by mass (*w/c*), is explored for a set of eleven different concrete mixtures prepared in the laboratory. In these mixtures, *w/c*, paste content, air content, fly ash content, high range water reducer dosage, and cement alkali content are all varied. Additionally, concrete electrical resistance data are supplemented by measuring the resistivity of its component pore solution obtained from five laboratory-prepared cement pastes with the same proportions as their corresponding concrete mixtures. Only measuring the concrete electrical resistance can provide a prediction of the mixture's paste content or the product *w*c*; conversely, when pore solution resistivity is also available, *w/c* and water content of the concrete mixture can be reasonably assessed.

Keywords

cement content, electrical resistance, formation factor, mixture proportions, paste content, porosity, resistivity, water-cement ratio, water content

Introduction

Performance-based quality control of concrete is an important objective of the ready-mixed concrete industry, and its customers including engineers and building owners. To assure fulfillment of its intended function, job-site measurements of concrete temperature, slump, density (unit weight), and air content are routinely performed following prescribed ASTM International standard test methods. Taken together, measurements of air content and density provide some indication that the mixture proportions of the concrete coming from the ready-mixed concrete truck are the same as the ones detailed in the job specifications.

Other tests to confirm the mixture proportions have long been sought, such as a microwave field test to estimate the water content of the delivered concrete [1–3]. As cementitious content is typically known from the batch tickets, the water-cement ratio (*w/c*) or water-cementitious materials ratio (*w/cm*) by mass could then be estimated. More recently, Mancio et al. [4] have shown the potential of using measurements of electrical resistivity to estimate *w/c* of concrete. In their study on eight concrete mixtures designed per the ACI 211.1 (*Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete*) procedures, *w/c* was varied only by changing the cement content (*c*) while keeping the water content constant. This ensured that the electrical resistivity increased with an increase in *w/c*, as for a higher *w/c* (lower cement content), there were fewer conductive ions being released by the reduced quantity of cement (per unit volume of concrete). Importantly, for potential field use of this technology, these authors also showed that "time did not have a statistically significant effect on the electrical resistivity of fresh concrete before initial setting" [4].

Based on this and other research [5,6], in 2015, ASTM subcommittee C09.60 (Testing Fresh Concrete) formed a task group to develop a standard practice for measuring the electrical resistance, *R*, of fresh concrete. (The draft document is currently under subcommittee balloting.) To support the development of this document, the present study examines the electrical resistance of eleven concrete mixtures along with the electrical resistivity of five of their component pore solutions.

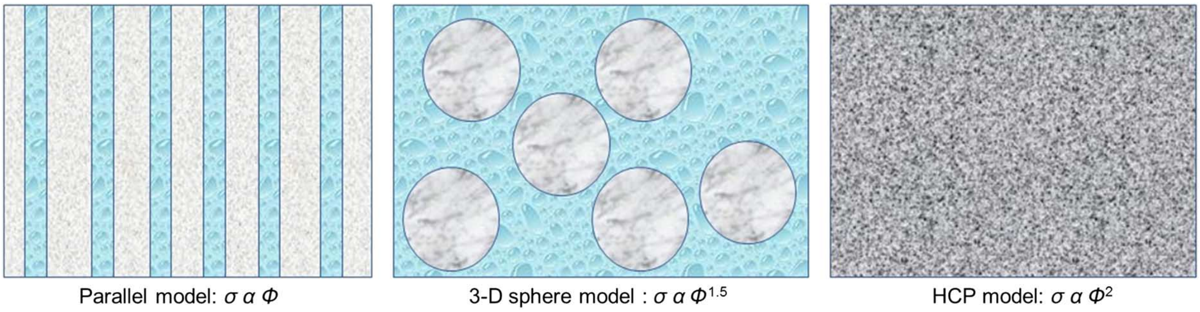
Viewing concrete as a conventional porous media and assuming nonconducting solids (aggregates, cement particles, supplementary cementitious materials [SCMs]), the measured electrical conductivity (σ) or resistivity (ρ) of a fresh concrete sample will be determined by the conductivity of the pore solution (σ_0; the major conducting component) and characteristics of the solution-filled porosity including pore volume fraction ($\varnothing$) and tortuosity/connectivity. The ratio of concrete conductivity to pore solution conductivity or, equivalently, pore solution resistivity (ρ_0) to concrete resistivity can be described using an equation of the following form [7]:

$$\frac{\sigma}{\sigma_0} = \frac{\rho_0}{\rho} = \frac{1}{F} = a \cdot \varnothing^n \quad \text{or} \quad \varnothing = \left(\frac{\rho_0}{a \cdot \rho}\right)^{\frac{1}{n}} \tag{1}$$

where *F* is the formation factor adapted from rock geology, *a* is a constant determined by pore geometry, and *n* typically takes on values between 1 and 2. In a fresh concrete, $\varnothing$ is directly proportional to the water content (*w*, water mass per unit volume of concrete), as the air voids are neither water-filled nor conductive. In a typical experiment, fresh concrete resistance (*R*) is measured directly. If desired, resistivity can then be calculated using a geometry factor, *K*, as the following:

$$\rho = KR \tag{2}$$

FIG. 1 Models for relating concrete conductivity (σ) to porosity (Φ).



In the above analysis, a single and constant temperature is assumed, because the measured resistance/resistivity is also a function of temperature [8].

Fig. 1 shows some possible values for *n*, varying from a lower bound of 1 for a simple parallel model through a value of 1.5 for a suspension of insulating particles in a 3-D conducting fluid [7] to a value of 2 for a hydrated cement paste or concrete specimen [9]. Here, Eq 1 will provide a basis for developing relationships between electrical resistance measurements and concrete mixture proportions. A change in mixture proportions will alter both the concrete resistance and the pore solution resistivity, as a lower *w/c* concrete will have a higher ionic concentration and hence a lower pore solution resistivity.

Research Significance

Assessment and control of the mixture proportions of ready-mixed concrete are a critical step in meeting project specifications and producing a quality structure. Measurements of the electrical resistance of fresh concrete may serve a valuable role in this process. Here, the potential and limitations of this technique are evaluated based on the measured properties of eleven different concrete mixtures prepared in the laboratory. The advantages of supplementing the electrical resistance of the fresh concrete with a measurement of the resistivity of its pore solution to effectively compute a formation factor are also explored.

Objective

The objectives of the present study are as follows:

1. Develop correlation curves between *w/c* (or *w/cm*) and measured resistance
   - at constant paste volume—when *w/c* is varied, both water and cement contents are varied
   - at varying paste volumes and constant cement content—when *w/c* is varied, only water content is varied

   The findings will help determine which alternative is more sensitive to a change in resistance. The draft ASTM practice allows for both options.
2. Compare immediately measured resistance values with those obtained after 90 min [4]
   - This will provide background on how to interpret field data versus lab data. Field resistance will typically be measured in the time frame of 45 to 90 min after mixing, whereas lab data can be measured immediately after mixing.

3. Investigate the impact of the following variables of concrete mixtures at the same *w/c* or *w/cm* on measured electrical resistance:
   - Change in paste volume
   - Use of 25 % Class F fly ash by volume in the mixture
   - Variation of the alkali content of the portland cement (i.e., a high-alkali cement)
   - Use of admixtures such as a high range water-reducing admixture (HRWRA)
   - Air entrainment
4. Develop single operator precision information.
5. Relate measured electrical resistance to mixture proportions based on Eq 1.

Materials and Methods

MATERIALS

The following materials were used in this study:

- ASTM C150, *Standard Specification for Portland Cement* [10], Type I/II portland cement (low alkali) with sodium oxide equivalent (Na_2O_{eq}) = 0.48 %
- ASTM C150 [10] Type I/II portland cement (high alkali) with Na_2O_{eq} = 0.90 %
- ASTM C618, *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete* [11], Class F fly ash
- ASTM C33, *Standard Specification for Concrete Aggregates* [12], No. 57 crushed coarse aggregate
- ASTM C33 [12] natural sand with a fineness modulus of 2.83
- ASTM C494, *Standard Specification for Chemical Admixtures for Concrete* [13], Type F polycarboxylate HRWRA
- ASTM C260, *Standard Specification for Air-Entraining Admixtures for Concrete* [14], inorganic air-entraining admixture

TARGET MIXTURE PROPORTIONS

To complete the objectives outlined above, an experimental design was developed consisting of ten unique concrete mixtures. As detailed in Table 1, in Mixtures 1, 2, and 3, the *w/c* was varied as 0.37, 0.42, and 0.47, respectively. The quantity of portland cement was maintained constant and the mixing water content was varied, thus allowing the paste volume to vary. In mixtures 2, 4, and 5 the *w/c* was again varied as 0.42, 0.37, and 0.47, respectively, but while maintaining the same paste volume. Mixture 6 had the same *w/c* as Mixture 3, but was proportioned at a lower paste volume. Mixture 7 included 25 % fly ash by volume of cementitious materials, with the same *w/cm* and paste volume as Mixture 2.

TABLE 1
Mixtures proportions [lbs/yd^3 (kg/m^3)].

Mixture No.	1	2	3	4	5	6	7	8	9	10
Low Alkali Cement	650 (386)	650 (386)	650 (386)	697 (414)	609 (361)	530 (314)	500 (297)		650 (386)	650 (386)
High Alkali Cement								650 (386)		
Fly Ash							138 (82)			
Water	241 (143)	273 (162)	306 (182)	258 (153)	286 (170)	249 (148)	268 (159)	273 (162)	306 (182)	273 (162)
Target Air, %	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	6.0
HRWRA, oz/cwt[a]	8.50	4.30	2.40	6.50	4.00	5.00	4.00	4.50	0.00	3.00
w/cm or *w/cm*	0.37	0.42	0.47	0.37	0.47	0.47	0.42	0.42	0.47	0.42
Paste Volume Fraction ($w+c$) or ($w+cm$)	0.265	0.285	0.304	0.285	0.285	0.248	0.285	0.285	0.304	0.285

Note: [a]Equivalent to 0.583 mL/kg.

Mixture 8 had the same *w/c* and paste volume as Mixture 2 but was produced using a high-alkali cement with an equivalent alkali content of 0.90 %. Mixture 9 had the same *w/c* and paste volume as Mixture 3, but the HRWRA was not used in this mixture. Mixture 10 was an air-entrained mixture with the same *w/c* and paste volume as Mixture 2. Because of an error in the preparation of Mixture 4, it had to be recast as Mixture 4R, hence, the total of eleven mixtures investigated in the present study.

The mixtures were all non–air entrained except for Mixture 10. The properties measured on the fresh concrete included slump (ASTM C143, *Standard Test Method for Slump of Hydraulic-Cement Concrete* [15]), air content using both the gravimetric and pressure test methods (ASTM C138, *Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete* [16], and ASTM C231, *Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method* [17]), temperature (ASTM C1064, *Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete* [18]), and density (ASTM C138 [16]), and two 4- by 8-in. (100- by 200-mm) cylinders were prepared for measuring compressive strength at 42 days (ASTM C39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens* [19]). Cylinders for compressive strength testing were demolded after 1 day and stored until the age of testing in a fog room maintained at 23°C ± 2°C.

The following procedures were used on Mixtures 1–3 to obtain information on single laboratory repeatability of the resistance measurements and to evaluate the impact of elapsed time. After the concrete was mixed following standard laboratory procedures [20], a sample of concrete was obtained for the fresh and hardened properties while the remaining concrete was retained in the mixer. Then, six nominally 4- by 8-in. (100- by 200-mm) concrete cylinders were prepared for the resistance measurements following ASTM Standard Practice C192/C192M, *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory* [20]. An electrode assembly was carefully inserted into the filled mold, any excess concrete was carefully removed from the top surface, the top surface was sealed with a lid, and the outside of the mold was tapped lightly 10 to 15 times using a wooden mallet. The resistance measurements were made on each cylinder by two operators using two sets of devices resulting in twelve resistance measurements for each mixture. The operators interchanged cylinders for measurements. These "initial" measurements of resistance were all conducted within 14 to 48 min after the time of first contact between cement and water. One cylinder was left connected to a measuring device to obtain a resistance measurement at 90 min. The concrete left in the mixer was covered to avoid evaporation and (re)mixed for 1 min every 5 min until about 90 min. A sample was obtained at 90 min from which three cylinders were prepared for resistance measurements. These resistance measurements were made between 86 and 109 min. For mixtures 4–10, three concrete cylinders were prepared for the resistance measurements and the resistance was measured by only one operator. No resistance measurements were made beyond 90 min on any of the concrete mixtures.

FRESH AND HARDENED CONCRETE MEASUREMENTS AT THE NATIONAL READY MIXED CONCRETE ASSOCIATION

Concrete mixture proportions and test results are provided in **Table 2**. Because Mixture 4 had been cast with an incorrect *w/c* of 0.39, Mixture 4R had to be cast with the correct *w/c* of 0.37. For all the mixtures, the measured slump varied between 2 in. (50 mm) and 9 in. (225 mm). HRWRA dosages (**Table 2**) were adjusted to keep the slump within this range. All concrete mixtures were readily consolidated into their cylinder molds, as certainly,

TABLE 2
Mixture proportions and test results.

Mixture ID	1	2	3	4	4R	5	6	7	8	9	10
Yield Adjusted Proportions											
Total Cementitious, lb/yd^3 (kg/m^3)	638 (379)	648 (384)	649 (385)	693 (411)	704 (418)	606 (360)	527 (313)	641 (380)	648 (384)	651 (386)	663 (393)
Low Alkali Portland Cement, lb/yd^3	638 (379)	648 (384)	649 (385)	693 (411)	704 (418)	606 (360)	527 (313)	503 (298)		651 (386)	663 (393)
High Alkali Portland Cement, lb/yd^3									648 (384)		
Fly Ash, lb/yd^3								138 (82)			
Coarse Aggregate (No. 57), lb/yd^3	1,807 (1,072)	1,836 (1,089)	1,840 (1,092)	1,831 (1,086)	1,859 (1,103)	1,834 (1,088)	1,830 (1,086)	1,852 (1,099)	1,836 (1,089)	1,843 (1,093)	1,879 (1,115)
Fine Aggregate, lb/yd^3	1,532 (909)	1,437 (853)	1,355 (804)	1,434 (851)	1,456 (864)	1,436 (852)	1,594 (946)	1,437 (853)	1,437 (853)	1,358 (806)	1,291 (766)
Mixing Water, lb/yd^3	237 (141)	272 (161)	305 (181)	267 (158)	260 (154)	285 (169)	247 (147)	269 (160)	272 (161)	306 (182)	278 (165)
HRWRA, oz/cwt[a]	8.65	4.30	2.48	6.50	8.50	1.87	5.00	5.09	4.50	0.00	3.00
w/c or *w/cm*	0.3713	0.42	0.47	0.3849	0.37	0.47	0.47	0.42	0.42	0.47	0.42
Paste Volume (V_{w+cm})	0.261	0.284	0.304	0.289	0.287	0.283	0.246	0.286	0.284	0.304	0.290
Fresh Concrete Properties											
ASTM C143, Slump, in. (mm)	8 ¼ (210)	3 ¾ (95)	5 ¼ (133)	8 (203)	8 (203)	4 ¼ (108)	3 (76)	5 (127)	5 ¼ (133)	3 ½ (89)	1 ¾ (44)
ASTM C138, Density, lb/ft^3 (kg/m^3)	156.1 (2,500)	155.3 (2,488)	153.7 (2,462)	156.5 (2,507)	158.5 (2,539)	154.1 (2,468)	155.5 (2,491)	155.5 (2,491)	155.3 (2,488)	154.0 (2,467)	152.3 (2,440)
ASTM C138, Gravimetric Air, %	3.8	2.3	2.1	2.6	1.1	2.4	2.6	1.4	2.3	1.9	4.1
ASTM C231, Pressure Air, %	2.9	2.5	2.4	1.8	1.6	2.4	2.8	1.9	2.1	2.0	4.2
ASTM C1064, Temperature, °F (°C)	72 (22)	72 (22)	72 (22)	70 (21)	70 (21)	70 (21)	70 (21)	70 (21)	70 (21)	70 (21)	70 (21)
Resistance Measurement											
Average resistance, Ω	39.3	36.8	33.4	35.0	37.7	37.7	47.3	46.0	24.0	36.0	36.0
Range, Ω	4.0	2.0	3.0	0.0	4.0	3.0	2.0	3.0	5.0	0.0	0.0
90 min Reading, Ω	38.0	36.0	32.0								
After 90 min Lab Mixing, Ω	44.0	38.0	32.3								
42d Strength (ASTM C39)											
Strength, psi (MPa)	11,250 (77.6)	9,300 (64.1)	7,470 (51.5)	10,200 (70.3)	11,460 (79.0)	7,010 (48.3)	8,370 (57.7)	8,320 (57.4)	7,540 (52.0)	6,470 (44.6)	6,660 (45.9)

Note: [a]Equivalent to 0.583 mL/kg

FIG. 2

Wireless device and setup to measure electrical resistance of fresh concrete.

improper or incomplete consolidation would surely influence the subsequent resistance measurements.

MEASUREMENT OF ELECTRICAL RESISTANCE OF FRESH CONCRETE

The wireless device used in this study for the measurement of electrical resistance of concrete is the SmartBox apparatus manufactured by Giatec[4] and is shown in Fig. 2. An alternating current is applied between the two electrodes inserted in the specimen, and the voltage is measured concurrently. The electrical resistance is calculated from the ratio of the measured voltage to the applied current and is directly reported by the device. In this study, the electrical resistance is measured on a 4- by 8-in. (100- by 200-mm) cylindrical specimen of the freshly mixed concrete. Using 0.5 % and 1 % by mass sodium chloride calibration solutions with reported resistivities of 1.22 $\Omega \cdot m$ and 0.625 $\Omega \cdot m$, respectively, at 20°C [21], a geometry factor, K, of 0.12 ± 0.1 m was determined for the experimental setup shown in Fig. 2. However, for the measurements performed on fresh concrete mixtures in this study, only resistance data are reported and analyzed, as these values were reported directly by the device and readily available to the end user.

PORE SOLUTION EVALUATION AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

Using the same low-alkali cement, fly ash, and HRWRA as employed for the concrete mixtures at the National Ready Mixed Concrete Association, five cement pastes were

[4]Certain commercial products are identified in this paper to specify the materials used and the procedures employed. In no case does such identification imply endorsement or recommendation by the National Institute of Standards and Technology (NIST) or the National Ready Mixed Concrete Association, nor does it indicate that the products are necessarily the best available for the purpose.

prepared at the National Institute of Standards and Technology (NIST). For the paste with 25 % fly ash, the cement and fly ash were preblended dry for 30 min in a 3-D mixer that allows the material to be tumbled and rolled simultaneously. Three of the pastes were prepared with a *w/c* of 0.37, 0.42, and 0.47, respectively, and a HRWRA dosage matching those of concrete mixtures 1, 2, and 3 in **Table 2**. The paste mixture with fly ash matched concrete Mixture 7 in **Table 2**. Finally, a *w/c* = 0.42 mixture without HRWRA was also prepared.

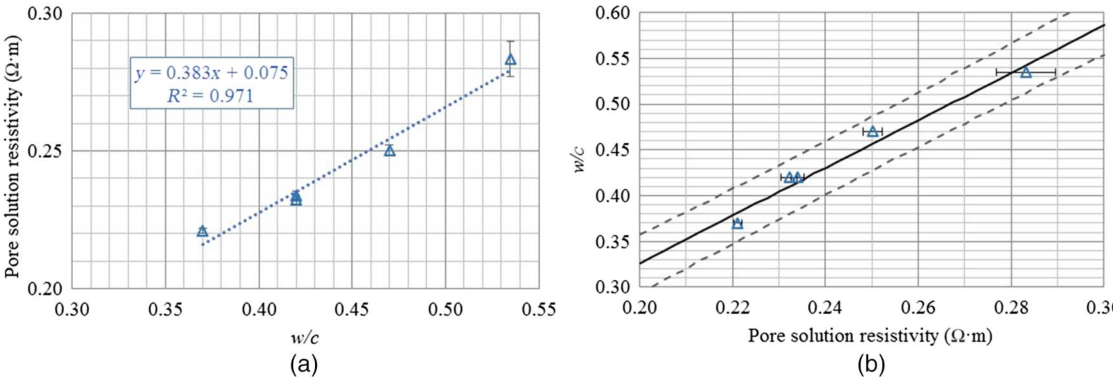
Pastes were prepared in a temperature-controlled high shear mixer following the procedures outlined in ASTM C1738, *Standard Practice for High-Shear Mixing of Hydraulic Cement Pastes* [22]. The cooling water bath attached to the mixing container was set at 15°C to obtain a paste temperature after mixing of between 21.5°C and 23.5°C. Pastes were sampled, at 30 ± 5 min after mixing, into two balanced centrifuge tubes (about 25 g of paste in each). These samples were centrifuged at 4,000 r/min (420 rad/s) for 3 min. The pore solution was carefully removed from the centrifuge tube. If the extracted solution was not transparent, a second round of centrifuging was performed, balancing its tube with an equally filled tube of water. The extracted pore solution was then placed in a small capillary (cylindrical) cell and its resistance measured using a commercial impedance analyzer housed in a walk-in environmental chamber maintained at 25°C ± 1°C. Calibration was performed by measuring the impedance response of a 0.1 mol/L solution of potassium chloride with a reference resistivity value of 0.78 Ω · m at 25°C [23]. Using the measured response of this solution, the computed K value of 4,420 m for the capillary cell was employed to convert the measured electrical resistances of the pore solutions in units of Ω to their corresponding resistivity values in units of Ω · m. Two to four resistivity measurements were made for each extracted solution.

Results

PASTE PORE SOLUTION RESISTIVITY RESULTS

The measured pore solution resistivities are plotted against the paste *w/c* in **Fig. 3**, along with the results from the calibration regression. The *w/cm* = 0.42 mixture with 25 % fly ash

FIG. 3 Measured pore solution resistivity versus *w/c* for pastes prepared with low alkali cement; (a) the estimated calibration function and (b) the estimated analysis function (inverse of the calibration function) with 95 % bounds are overlaid. In both, error bars indicate plus or minus one standard deviation for either 2 (*w/c* = 0.42 and 0.47) or 4 (*w/c* = 0.37 and 0.535 and *w/c* = 0.42 with no HRWRA) repeat measurements on the same solution sample. For (b), the 95 % bounds represent the uncertainty in the predicted value of *w/c* for a specified value of pore solution resistivity.



by volume corresponds to a $w/c = 0.535$, the rightmost data point in the figure. A strong linear relationship between *w/c* and measured resistivity is observed, with *w/c* within the range of 0.35 to 0.55 being predictable to within about ±0.015 via this electrical measurement, per a calibration regression analysis [24] performed in the statistical computing package *R*, using a Monte Carlo simulation with 10,000 trials conducted at each simulated value of resistance (0.015 representing the average uncertainty in the predicted *w/c* for resistivities in the range of 0.20 Ω · m to 0.30 Ω · m). One would expect the pore solution conductivity to be proportional to the number of charge carriers per unit volume of solution [25], implying a direct linear proportionality between *c/w* and conductivity, with different coefficients for each individual cement (binder). This would be equivalent to the observed linear relationship between their respective inverses, *w/c* and resistivity, observed in **Fig. 3**. The overlapping of the two data points for $w/c = 0.42$ indicates that the presence or absence of the HRWRA did not significantly influence the measured pore solution resistivity for the materials employed in this study. The values in **Fig. 3** are in reasonable agreement with those predicted by the NIST pore solution conductivity model based on the cement composition (equivalent alkalis) and mixture proportions [25,26], if it is assumed that about 55 % of the alkalis present in the cement are readily soluble upon contact with water (75 % is the default assumption in the NIST model) and that the alkalis provided by the fly ash used in this study are negligible.

RELATING ELECTRICAL RESISTANCE OF FRESH CONCRETE TO MIXTURE PROPORTIONS

Concrete Measurements Only

In **Table 2**, the resistance measurements of Mixtures 1–3 are an average of twelve readings, whereas the resistance measurements on Mixtures 4–10 are an average of three readings. The complete set of raw data as well as a greater discussion of the results can be found in Obla et al. [27]. The following observations can be made.

Fig. 4 shows a correlation between measured resistance, compressive strength, and *w/c* for Mixtures 1, 2, and 3. For these three mixtures, a reduction in *w/c* corresponded with a reduction in mixing water content that resulted in fewer pathways for the transport of the charged ions and therefore increased resistance. Having fewer pathways overcame the reduction in pore solution resistivity (**Fig. 3**) when the *w/c* was decreased. A reduction in *w/c* from 0.47 to 0.37 resulted in a small increase in measured resistance of about

FIG. 4

42-day compressive strength and fresh concrete electrical resistance versus *w/c* for Mixtures 1, 2, and 3; 1,000 psi is equivalent to 6.89 MPa. Ranges are provided in **Table 2**.

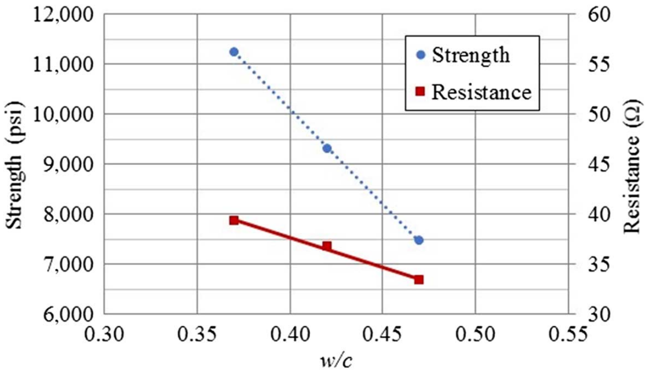
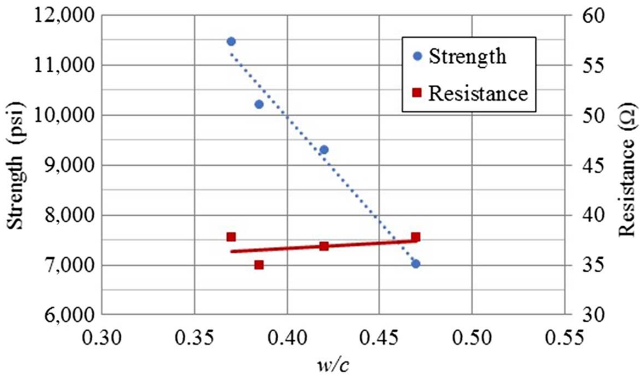


FIG. 5

42-day compressive strength and fresh concrete electrical resistance versus *w/c* for Mixtures 2, 4, 4R, and 5; 1,000 psi is equivalent to 6.89 MPa. Ranges are provided in **Table 2**.



18 % and a much higher increase of about 51 % in 42-day compressive strength. For the data shown in **Fig. 4**, linear fits to both resistance and compressive strength versus *w/c* yielded coefficients of determination (R^2) that were very close to 1.

Fig. 5 shows a similar plot of measured resistance and compressive strength versus *w/c* for Mixtures 4R, 4, 2, and 5. Because paste volume is kept constant for these mixtures, as the *w/c* decreased, the water content decreased, while cement content also increased. This resulted in fewer pathways for more charged ions. These two opposing factors resulted in only a small decrease in the measured resistance as *w/c* was decreased. This suggests that when developing a laboratory correlation between resistance and *w/c*, maintaining a constant paste volume may produce less of a change in electrical resistance than when the paste volume is varied. Strength is a better predictor of *w/c* than measured resistance for these mixtures, although it was not measured until 42 days after casting and therefore could not be employed as an onsite immediate quality control procedure. For the data shown in **Fig. 5**, while the coefficient of determination remains at 0.98 for the compressive strength data, it is only 0.14 for the resistance data.

Reducing the paste volume (Mixture 6) while maintaining the same *w/c* as in Mixture 2 resulted in a 42 % increase in measured resistance. Including 25 % Class F fly ash by volume of cementitious materials (Mixture 7) while maintaining the same *w/cm* as in Mixture 2 resulted in a 25 % higher measured resistance. In both cases, the higher measured resistance was likely due to the reduced cement content that contributed less charged ions to the pore solution. Additionally, in the first case, the lower mixing water content also contributed to the increased resistance.

Using a high alkali cement (Mixture 8), while maintaining the same *w/c* as in Mixture 2, resulted in a 35 % lower measured resistance. Unfortunately, the same sample of high alkali cement was not available for pore solution resistivity testing. In comparison, the NIST pore solution conductivity model [25,26] predicts that the high alkali cement mixture would have a 43 % lower pore solution resistivity than the low alkali cement mixture, if the extent of soluble alkalis were the same for both. Neither the non-use of the HRWRA (Mixture 9) nor the use of air entrainment (Mixture 10) significantly influenced the measured resistance. Readings after 90 min of simulated mixing are higher than those taken at 90 min on initially cast specimens for the lowest *w/c*, but similar for the two higher *w/c*. Additionally, the readings taken at 90 min on initially cast specimens were within 4 % of their original values.

The single operator standard deviation for the resistance measurement was determined to be 1.4 Ω, based on the worst case (Mixture 1). The single-operator coefficient of variation was 3.9 %. The average resistance of the mixtures evaluated varied between 24 Ω and 47 Ω. Therefore, the results of two properly conducted tests by the same operator on specimens prepared from the same sample of concrete are not expected to differ by more than 4 Ω or 10.8 % of the average in more than 95 % of the cases. Based on the precision statement of the slump test and the specified tolerances for slump in ASTM C94, *Standard Specification for Ready-Mixed Concrete* [28], it seems appropriate to suggest a tolerance of ±4 Ω to the specified value if this test were to be used as an acceptance test. If these tolerances are overlaid on average data from Mixtures 1, 2, and 3, considerable overlap will be created, suggesting that it would be difficult to distinguish between 0.37 and 0.47 *w/c* concrete mixtures using a single resistance measurement. So even if the only variable between different batches is the mixing water content as in Mixtures 1–3, the precision and the sensitivity of the test needs to be improved before it could be used as a reliable estimator for the *w/c* or *w/cm*.

Fig. 6 shows that the measured fresh concrete electrical resistance has basically no correlation with *w/c* (*w/cm*) when variables such as paste volume, dosage of SCM, and cement alkali content are varied. **Fig. 7** shows the inverse of resistance (or conductance) for all of the mixtures containing low alkali cement plotted against either the volume of cement or the volume of water or the volume of cement and water in a cubic yard of concrete. An increase in either cement or water volume led to a decrease in resistance (more ions and more pathways, respectively), however, the measured resistance correlated best with the sum of cement and water volumes.

Returning to Eqs 1 and 2, the measured concrete resistance should be proportional to the resistivity of the pore solution divided by (the water-filled porosity raised to the power of n) or (ρ_0/w^n). Because **Fig. 3** shows that pore solution resistivity is proportional to *w/c*, one might expect that the concrete resistance would then be proportional to $1/(c \cdot w^{n-1})$. For $n = 1$, the proportionality would simply be to $1/c$, proportional to the volume of cement fit shown by the leftmost data set in **Fig. 7**. For $n = 2$, the proportionality would be to $1/(c \cdot w)$, whereas for $n = 1.5$ (spherical inclusion case in **Fig. 1**), it would be to $1/(c \cdot w^{0.5})$. Scaled versions of these latter two relationships are plotted in **Fig. 8** along with

FIG. 6

w/c (*w/cm*) versus measured fresh concrete resistance for all mixtures.

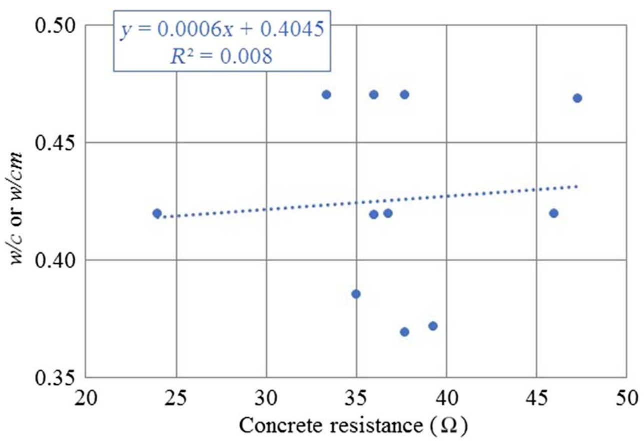
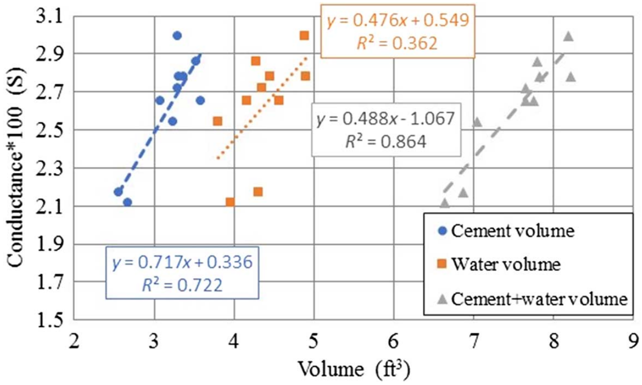


FIG. 7

Conductance (inverse of resistance) versus volume of cement, water, or cement and water for all concrete mixtures prepared with the low alkali cement. 1 ft^3 = 28.3 L.



one based on the inverse of the (cement + water) volume, or $1/(w + c/3.15)$, where 3.15 represents the specific gravity of the cement used in this study. Linear fits with a coefficient of determination greater than 0.9 are obtained for relating resistance to the inverse of $c \cdot w^{n-1}$ for either $n = 1.5$ or 2, while a coefficient of determination of 0.722 was obtained for $n = 1$ in **Fig. 7**. This suggests that the measured electrical resistance of fresh concrete can potentially provide information on the product of cement and water contents, or perhaps their sum (as indicated by the [cement+water] volume in **Fig. 7** and by the $3{,}000/[w + c/3.15]$) scaled paste volume data in **Fig. 8**, although it does not uniquely relate to *w/c* or either *w* or *c* separately. The relationships shown in **Fig. 8** would only be valid for concretes prepared with the low alkali cement and aggregates employed in this study, as any change in materials would require additional measurements to develop a new set of lines.

Concrete and Pore Solution Measurements

In this study, in addition to measuring the fresh concrete's electrical resistance, the resistivity of its component pore solution was also available in some cases (low alkali cement). For these, per Eqs 1 and 2, the ratio of pore solution resistivity to concrete resistance

FIG. 8

Resistance versus various combinations of water (*w*) and cement (*c*) contents. Cement +water volume is given by $1/(w+c/3.15)$. Independent variable values on the *x*-axis have been appropriately scaled to cover a similar range on a single plot.

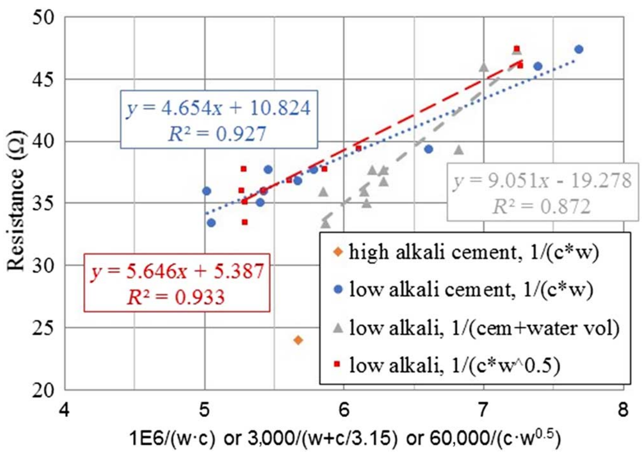
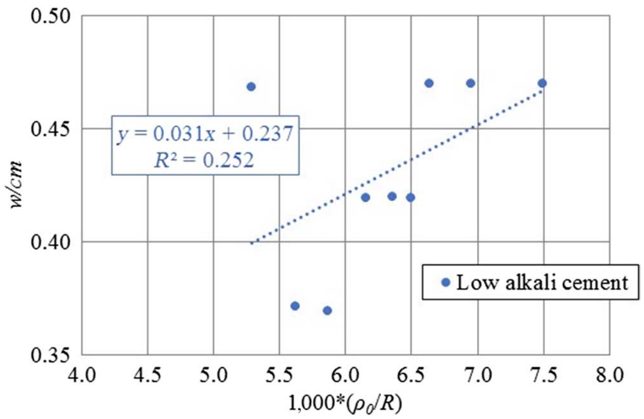


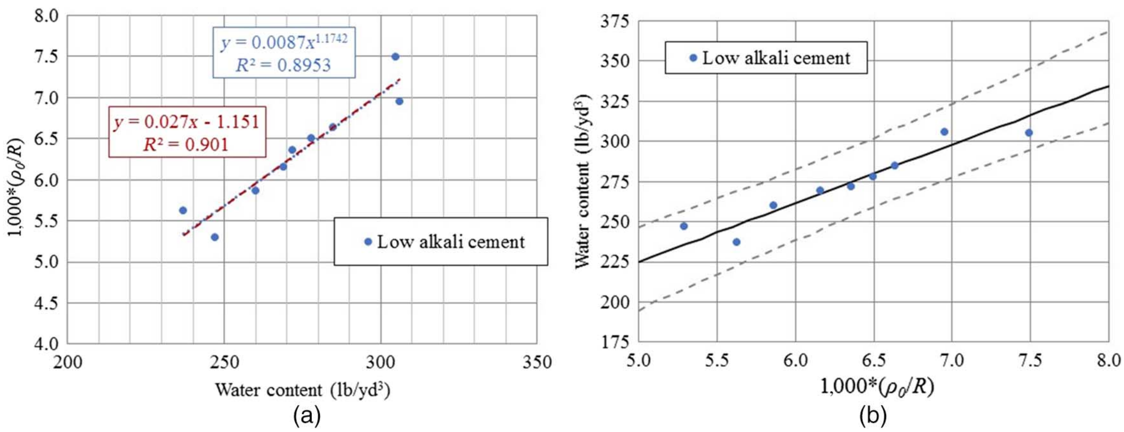
FIG. 9

w/cm versus scaled ratio of pore solution resistivity (ρ_O) to fresh concrete resistance (R).



should be directly proportional to the water content of the concrete (w) raised to the power of n. Thus, while a plot of mixture *w/cm* versus this resistance ratio only exhibits a weak correlation (**Fig. 9**), the relationship between water content (w) and the ratio is much better defined (**Fig. 10**). In the latter case, a linear fit ($n=1$, parallel model) provides a reasonable fit to the data, as does a power law model with $n=1.17$. This suggests that electrically, the fresh concrete behaves somewhere in between the parallel (e.g., bleed channels) and the 3-D spherical inclusion models shown in **Fig. 1**. Based on the data in **Fig. 10**, either of these models could be applied in a predictive manner to use a measured electrical resistance ratio to predict the water content of the concretes prepared in this study. For the linear model, Monte Carlo–based predictions (generated using R) are shown in the right plot in **Fig. 10**; the average uncertainty in the predicted water content is computed to be about 12.5 lb/yd^3 (7.4 kg/m^3).

FIG. 10 Scaled ratio of pore solution resistivity to fresh concrete resistance versus water content with (a) estimated calibration functions and (b) the estimated analysis function for the linear model with 95 % bounds overlaid. The bounds represent the uncertainty in the predicted value of water content for a specified ratio of pore solution resistivity to fresh concrete resistance; 1 lb/yd^3 is equivalent to 0.593 kg/m^3.



Conclusions and Prospectus

This study has indicated that the electrical resistance of fresh concrete, while not directly related to its *w/c* or *w/cm* ratio, can be related in an inverse fashion to volumetric paste (cement + water) content or some multiplicative combination of water and cement contents ($c \cdot w^n$) for concretes prepared with a given set of materials. With a concurrent measurement of the pore solution resistivity, it was possible to estimate the water content of the fresh concrete with a computed uncertainty of 12.5 lb/yd^3 (7.4 kg/m^3) for the low alkali cement concretes examined in this study. Additionally, direct measurement of the pore solution resistivity on corresponding pastes allowed an estimation of *w/c* with a computed uncertainty of 0.015. The results here have indicated that even when the only variable between different batches is the mixing water content, the precision and the sensitivity of the test needs to be improved further before it can be used as a reliable estimator of mixture proportions (quality control). However, the general insensitivity of the measured electrical resistance values to the presence of the admixtures employed in this study and (hauling) time within 90 min are encouraging results for promoting continued development of the method. Further studies are needed to examine the range of validity of the relationships proposed here, not only in terms of a wider range of mixture proportions but also covering the range of temperatures likely to be encountered in the field during concrete construction. Additionally, possibilities to extract concrete pore solution and measure its electrical resistivity in the field need to be explored.

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