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Instantaneous In-Situ Determination of Water-Cement Ratio of Fresh Concrete

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*The water-cement ratio (*w/c*) is one of the most important parameters determining the quality of cement-based materials. Currently, there is no practical way to accurately determine this ratio after all the ingredients of concrete have been mixed, posing a significant quality-control problem for the construction industry. A new method has been developed to address this challenge whereby an electrical resistivity probe is immersed in fresh concrete, providing an instantaneous and accurate measure of a concrete's* w/c*. Experiments were conducted on eight concrete mixtures designed according to the ACI 211.1 procedure, with varying* w/c *(0.30, 0.40, 0.50, and 0.60) and fly ash percentages (0 and 25%). The results demonstrate a strong direct correlation between the resistivity of fresh concrete and the* w/c*. Average* w/c *estimates based on measurements using the resistivity probe were within ±0.01 of the actual values for all mixtures tested.*

Keywords: durability; electrical resistivity; fresh concrete; nondestructive testing; quality assurance; quality control; strength; water-cement ratio.

INTRODUCTION

Instantaneous, in-situ measurement of the water-cement ratio (*w/c*) of fresh concrete is an unresolved challenge that has motivated engineers and researchers for several decades. A number of studies have explored various methods for determining the *w/c* of concrete.[1] In 1977, the U.S. Army Corps of Engineers developed a technique based on chloride and calcium titration to determine, respectively, the water and cement contents of fresh concrete.[2] In 1998, Popovics and Popovics[3] explored applying ultrasonic pulses to both fresh and rapidly solidified concrete. Other strategies have included separating the components of concrete: in 1980, Nägele and Hilsdorf[4] attempted to separate cement by flotation; in 1970, Bavelja[5] developed a pressure-filter method of separating water from cement; and in 1955, Hime and Willis,[6] tried to separate cement using a centrifuge. In 1994, the Kansas Department of Transportation continued Bavelja's[5] work in pressure-sieving fresh concrete by using a turbidimeter to correlate the turbidity of the remaining solution to the *w/c*.[7] In 1990, The National Cooperative Highway Research Council investigated applying solvents to determine the *w/c* and developed an acetone moisture content method, in addition to the use of a specific ion electrode (bromide) to identify the presence of some common ions from cement[8]; but the results were not promising.

A nuclear gauge method developed in 1993 by Troxler Electronic Laboratories provided accurate results; however, only trained professionals can operate the nuclear device, which has limited the method's acceptance and widespread use.[1,9,10] In the microwave method, perhaps one of the most practical methods developed thus far, a sample of fresh concrete is weighed and then heated in a microwave oven to evaporate the water. The weight difference between the dry and wet samples yields the water percentage, and the *w/c* can be calculated when the information is combined with the cement content from the mixture design specifications.[11,12] The microwave test is a relatively simple method, but with a few important limitations. It only measures the water amount, takes between 15 to 30 minutes to dry a concrete sample, and safety concerns regarding the presence of metal in some aggregates remain an issue.[13]

Despite many innovative attempts to measure the *w/c* of fresh concrete, the industry has failed to agree on a single, simple and efficient method that can provide instantaneous and accurate results. Currently, none of the methods listed has gained widespread acceptance for use in field conditions, and the slump flow remains the most commonly specified test to evaluate the quality and determine acceptance of fresh concrete at a building site.

Electrical resistivity and *w/c* of wet mixtures

There have been two significant efforts to describe the *w/c* of fresh cement paste and concrete mixtures from electrical resistivity measurements.[10,14] Wei and Li[14] studied the early hydration process of portland cement pastes using resistivity measurements conducted in a non-contacting device.[15] In their setup, cement paste was cast into a ring-shaped mold with a rectangular cross section, and an electrical current flow was induced in the specimen by an external transformer. Li's[14] group characterized the bulk electrical resistivity of fresh cement pastes mixed with different *w/c*, as well as the electrical resistivity of pore solutions extracted from the cement pastes by vacuum filtering. Based on their results, Wei and Li[14] suggested that electrical resistivity measurements can be used to determine the *w/c* of fresh cement pastes; however, no experiments with concrete or mortar were performed. Their study provides valuable insight into the mechanisms of cement hydration, particularly regarding the dissolution of ions into solution and their relationship to electrical resistivity. The results, however, have limited applicability when the electrical resistivity of concrete is considered.

Although cement paste (cement plus water) is an essential component of concrete, concrete is a composite material that necessarily includes aggregates (typically fine and coarse) and often mineral and/or chemical admixtures. Cement paste and concrete have markedly different properties and behavior, both in the fresh (wet) and hardened states, primarily due to the presence of aggregates in concrete.

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According to Archie's law, the bulk electrical resistivity of porous media is a function of two parameters: 1) resistivity of the pore fluid; and 2) porosity[16,17]

$$\rho_b = \frac{\rho_f}{a\phi^m} \quad (1)$$

where ρ_b is bulk electrical resistivity, ρ_f is the resistivity of the pore fluid, ϕ is the porosity (by volume), and a and m are empirical constants.

In fresh cement pastes (a solution-saturated porous media), porosity (or water content) varies significantly with the *w*/*c* and has a strong influence on the bulk resistivity. In fresh concrete, as discussed in more detail as follows, fresh mixtures with different *w*/*c* may have very similar "porosities" or overall water content.[18] In fact, according to ACI's standard concrete mixture-proportioning procedure (ACI 211.1), for a given aggregate size and consistency (slump), different concrete mixtures can have essentially the same overall water content (lb/yd^3 [kg/m^3]) independent of the *w*/*c*, which is chosen based on the desired compressive strength.[19,20]

MacDonald and Northwood[10] attempted to characterize the relationship between the *w*/*c* and electrical resistivity of fresh concrete. Samples for resistivity testing were prepared by sieving wet concrete through a No. 4 (4.75 mm) screen, and resistivity measurements were conducted on the mortar fraction of concrete. After sieving, the wet mortar samples were cast into cylindrical molds and placed in a bench-top measuring circuit. Even though the aggregate size was kept constant in all mixtures tested, the consistency and, consequently, the water content of the different mixtures varied significantly. Careful analysis of their results reveals that the variation of electrical resistivity observed was primarily caused by changes in porosity, which is approximately equal to water content in the fresh state, and not changes in the concrete's *w*/*c*. Note that in construction practice, the slump of concrete (a measure of consistency) is specified based on the type of construction and the slump range is typically fixed for a given job.[19] The study by MacDonald and Northwood[10] also included an exploration of the diffusivity of chloride ions in concrete, and the authors ultimately concluded that it is possible to estimate the diffusivity of hardened concrete by measuring its resistivity. The researchers did not recommend electrical resistivity measurements as a means for estimating the *w*/*c* of fresh concrete and noted that additional work would be required to develop a field procedure.

Fig. 1—Electrical resistivity probe developed in this study. (Note: Electrode spacing is 1 in. [2.5 cm].)

RESEARCH SIGNIFICANCE

Potential quality problems of a given concrete batch can usually be detected only after the material has hardened in the structure, when compressive strength experiments are performed. Remediation costs, including material, safety, labor, and time delays, can be substantial. Considering that existing methods for determining the *w*/*c* of fresh concrete are cumbersome and often unreliable,[21] new user-friendly, accurate techniques should be investigated. The objective of this research is to devise an efficient method and instrument to instantaneously determine the *w*/*c* of fresh concrete in the field.

EXPERIMENTAL INVESTIGATION

Experimental setup

An electrical resistivity measuring device was designed and constructed for this project. The apparatus is based on a four-electrode probe using a Wenner array, a well-established electrode array typically used in exploration geophysics. The probe consists of four stainless-steel electrodes separated at a distance of 2.5 cm (1 in.) by a nonconductive plastic body (Fig. 1).

The laboratory testing system consists of a power supply, a resistor of known resistance (R_o = 160 Ω), and the resistivity probe that is connected in series (Fig. 2). The two outer electrodes of the probe are connected to the circuit, and the power supply drives an AC current with a 1.5 V, 1 kHz sinusoidal wave. In this study, a bench-top power supply was used; however, a battery-operated handheld function generator could easily be substituted in a field instrument. The user submerges the probe into a fresh concrete sample and a current flows through the material. As shown in Fig. 2, voltmeters connected in parallel with both the known resistor and the inner electrodes display the corresponding voltage drops across these elements (V_o and V_c).

The current I_o passing through the circuit is given by V_o/R_o, and the electrical resistance of the concrete sample R_c is equal to V_c/I_o. The electrical resistivity of the concrete ρ_c, a

Table 1—Concrete mixture proportions

Mixture no.	*w/c*	Unit proportions				Amounts (SSD), kg/m^3 (lb/yd^3)				
		Cement	Fly ash	FA	CA	Cement	Fly ash	Water	FA	CA
1	0.30	1.00	—	0.84	0.91	722 (1217)	—	217 (365)	557 (939)	858 (1446)
2	0.40	1.00	—	1.41	1.21	541 (913)	—	217 (365)	710 (1197)	858 (1446)
3	0.50	1.00	—	1.97	1.52	433 (730)	—	217 (365)	802 (1352)	858 (1446)
4	0.60	1.00	—	2.54	1.82	361 (608)	—	217 (365)	863 (1455)	858 (1446)
5	0.30	0.75	0.25	0.84	0.91	541 (913)	180 (304)	217 (365)	557 (939)	858 (1446)
6	0.40	0.75	0.25	1.41	1.21	406 (684)	135 (228)	217 (365)	710 (1197)	858 (1446)
7	0.50	0.75	0.25	1.97	1.52	325 (548)	108 (183)	217 (365)	802 (1352)	858 (1446)
8	0.60	0.75	0.25	2.54	1.82	271 (456)	90 (152)	217 (365)	863 (1455)	858 (1446)

Notes: FA is fine aggregate; CA is coarse aggregate; specific gravity of materials: cement = 3.15, fly ash = 2.60, and CA = 2.68.

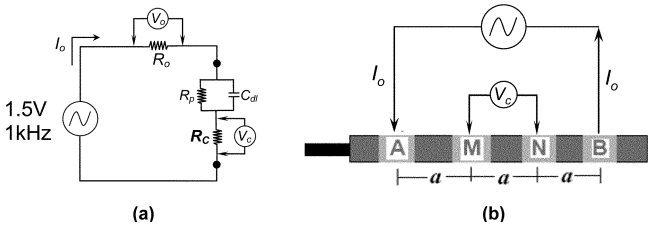

Fig. 2—Schematic illustrations of: (a) electric circuit; and (b) resistivity probe.

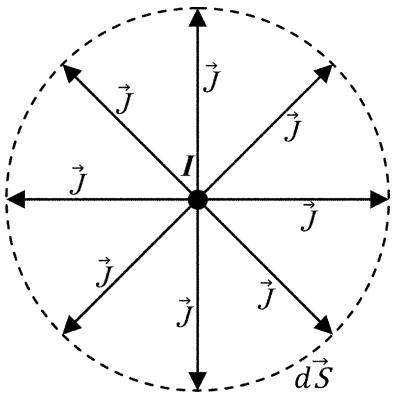

Fig. 3—Point source of current I *in spherical whole space.*

material property independent of sample geometry, is given by $\rho_c = kR_c$, where k is the geometric factor (a parameter determined by the geometry of the probe used). As described in more detail in the following, the geometric factor for this resistivity probe immersed in solution has been analytically determined as $k = 4\pi a$, where a is the spacing between electrodes. Experimental verification of the calculated geometric factor was also carried out. To experimentally determine the value of this constant, the probe was submerged in aqueous solutions of known resistivities ($\rho_s \approx 1$ Ω-m, 5 Ω-m, and 10 Ω-m), and the expression $k = \rho_s/R_s$ was used to obtain the geometric factor. In this equation, R_s is given by V_s/I_o, that is, the potential measured across the two inner electrodes divided by the current driven through the circuit.

Relationship between *w/c* and electrical resistivity of fresh concrete

To investigate the relationship between electrical resistivity and the *w/c* of fresh concrete, eight samples with varying *w/c* (0.30, 0.40, 0.50, and 0.60) and fly-ash percentages (0 and 25% of Type I/II cement replaced with Class F fly ash) were prepared according to the ACI 211.1 mixture design procedure.[19] Details of the concrete mixtures are presented in Table 1. Note that because water content is a function of the desired workability and aggregate characteristics, concretes with the same slump but different *w/c* typically have similar water content per unit volume. Based on the ACI procedure, a non-air-entrained concrete with a maximum aggregate size of 1/2 in. (12.5 mm) and 3 to 4 in. (75 to 100 mm) slump, as used in this research, will have a mixing water content of approximately 365 lb/yd^3 (216 kg/m^3).[19] To avoid possible variations because of changes in tap-water resistivity, the initial resistivity of the mixing water was measured and kept constant at 80 Ω-m. Immediately after mixing, a portion of each concrete was poured into a 6 x 12 in. (15 x 30 cm) plastic cylinder to hold the sample as resistivity measurements were conducted over time. Standard for all measurements, the probe was vertically immersed in concrete and centrally located within the plastic cylinder. Before initial setting of the cement, resistivity was measured at 10-minute intervals for approximately 2 hours.

ANALYTICAL INVESTIGATION

Theoretical determination of geometric factor *k*

The geometric factor for a Wenner electrode array in a homogeneous half space (as used in exploration geophysics and surface measurements in general) is known to be equal to $2\pi a$.[17,22] In our application, however, the resistivity probe is completely immersed in the surrounding medium. As current flows through the circuit and the concrete from electrode A to B (refer to Fig. 2(b)), electrode A can be thought of as a point source of current in a spherical whole space, as illustrated in Fig. 3. The current I flowing through this sphere can be expressed as

$$I = J \cdot 4\pi r^2 \tag{2}$$

where J is current density and $4\pi r^2$ is the surface area of the spherical whole space. Because electrical conductivity ($\sigma = 1/\rho$) is defined as the ratio between current density J and electric field E, and considering that the electric field at a point is equal to the negative gradient of the electric potential ϕ, the expression above can be rewritten as

$$I = \sigma E \cdot 4\pi r^2 = \sigma \cdot (-\nabla\phi) \cdot 4\pi r^2 \tag{3}$$

In this equation, ϕ is a scalar quantity representing the electric potential at a single point. Expressing the electric

potential gradient in spherical coordinates ($\nabla\phi = d\phi/dr$) and integrating the resulting expression, the electric potential at a point on the spherical surface (ϕ) can be expressed as a function of the current I, resistivity ρ, and radius of the whole space r.

$$\phi = \frac{I}{\sigma \cdot 4\pi r} + C = \frac{I \cdot \rho}{4\pi r} + C \quad (4)$$

Electric potential cannot be measured at a single point, but only as the difference between two points. For the resistivity probe used in this study (Fig. 2(b)), the electric potential at each of the two inner electrodes (M and N) is a function of the current flowing from the two outer electrodes (A and B). As schematically represented in Fig. 4, the potential at electrode M, for example, is given by the difference between potentials of the two outer electrodes (A and B), located at distances a and $2a$, respectively, from M. The potential at electrode M (ϕ_M) is then given by

$$\phi_M = \frac{I_A\rho}{4\pi a} - \frac{I_B\rho}{4\pi(2a)} \quad (5)$$

Similarly, the potential at electrode N is

$$\phi_N = \frac{I_A\rho}{4\pi(2a)} - \frac{I_B\rho}{4\pi(a)} \quad (6)$$

Considering that the current flowing through electrode A is the same as through electrode B ($I_A = I_B = I$), subtracting the two potentials ($\phi_M - \phi_N$) yields the potential measured across the two inner electrodes (V)

$$V = \frac{I \cdot \rho}{4\pi a} \quad (7)$$

Solving this expression for resistivity (ρ), results in

$$\rho = \frac{V}{I}(4\pi a) = R \cdot k \quad (8)$$

where $k = 4\pi a$ is the probe's geometric factor.

Therefore, knowing the electrode spacing (a) and the electric current (I) injected through the probe, the resistivity of the material can be directly obtained by simply measuring the voltage across the two inner electrodes. A resistivity reading can be obtained in as little as a few milliseconds, an instantaneous determination for all practical purposes.

As described in the following section, the calculated geometric factor k for our probe, which equals 0.319 (a = 1 in. [0.0254 m]), was very similar to the experimental value (less than 2.5% difference).

RESULTS AND DISCUSSION

Experimental determination of geometric factor *k*

The empirical determination of the probe's geometric factor was based on 18 measurements conducted with aqueous solutions of low, medium, and high electrical resistivity (refer to Table 2). The average measured value for k was 0.327, which is only 2.5% higher than the theoretical value calculated previously. This small error may be attributed to inaccuracies in resistivity measurements and the fact that point-sources of current were assumed in the theoretical calculation.

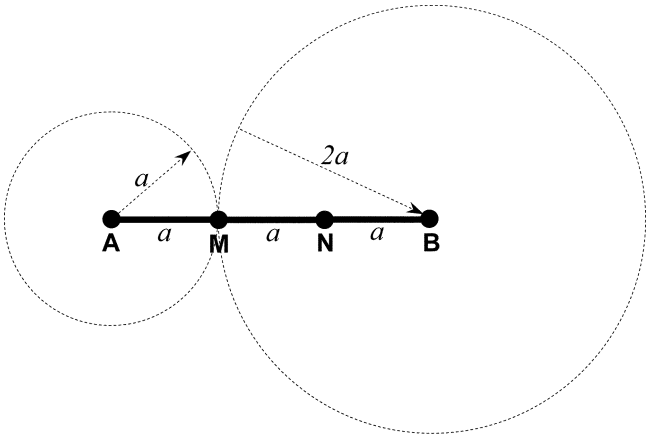

Fig. 4—Electric potential measured at inner electrode M is determined by difference between single-point potentials at outer electrodes A and B.

Table 2—Empirical determination of probe's average geometric factor *k*

Solution type	No.	ρ(Ω – m)	k_1	k_2
Low ρ (≈1 Ω-m)	1	0.93	0.315	0.313
	2	0.98	0.351	0.351
	3	0.90	0.360	0.361
Medium ρ (≈5 Ω-m)	4	4.55	0.303	0.304
	5	4.55	0.290	0.291
	6	4.50	0.334	0.335
High ρ (≈10 Ω-m)	7	9.35	0.330	0.296
	8	9.52	0.330	0.342
	9	9.90	0.336	0.335
Average geometric factor			0.327	
Standard deviation			0.023	

Both calibration and concrete resistivity measurements were obtained by vertically embedding the probe in the center of the sample, which was the standard 6 x 12 in. (15 x 30 cm) plastic cylinders typically used for compressive strength testing. Measurements taken off-center and close to the cylinder wall are influenced by the difference in conductivities between the concrete and the plastic container and should be avoided.

It is worth noting the geometric factor k is a constant that depends solely on the geometry of the resistivity apparatus, and it needs to be determined only once—at the product development stage.

Relationship between *w/c* and electrical resistivity of fresh concrete

Resistivity measurements were made at 10-minute intervals for each of the eight different samples during the first 2 hours after mixing. Two measurements were made at each time interval, and average values for each mixture were calculated including all readings made during the testing period. All measurements were made using the probe apparatus described previously. Tables 3 and 4 present the average resistivity values measured as a function of *w/c* for each of the mixtures, whereas Fig. 5 and 6 illustrate the relationship between the *w/c* and the electrical resistivity of fresh

Table 3—Relationship between *w/c* and electrical resistivity of fresh concrete (0% fly ash)

w/c	Average ρ (Ω-m)	Standard deviation	Coefficient of variation, %
0.30	3.07	0.122	3.96
0.40	4.13	0.138	3.34
0.50	4.88	0.165	3.47
0.60	5.29	0.188	3.56

Table 4—Relationship between *w/c* and electrical resistivity of fresh concrete (25% fly ash)

w/c	Average ρ (Ω-m)	Standard deviation	Coefficient of variation, %
0.30	4.15	0.087	2.10
0.40	5.52	0.192	3.30
0.50	6.47	0.203	3.07
0.60	7.16	0.415	6.41

Table 5—Electrical resistivity of concrete as function of time and *w/c*

	Resistivity (Ω-m) for different mixtures			
Time, minutes	0.30	0.40	0.50	0.60
0	2.22	2.91	3.39	3.98
10	2.19	3.25	3.59	4.12
20	2.27	3.01	3.60	4.05
30	2.20	3.08	3.52	4.03
40	2.10	2.91	3.68	3.83
50	2.06	2.96	3.68	3.85
60	2.15	2.95	3.61	3.79
70	2.08	2.92	3.51	3.61
80	2.19	2.92	3.47	3.68
90	2.33	2.81	3.50	3.74
100	2.34	2.87	3.41	3.79
110	2.27	2.97	3.35	3.64
120	2.21	2.84	3.36	3.63

concrete. As expected, the electrical resistivity of fresh concrete increased with increasing *w/c* (quite differently than occurs with hardened concrete). At a lower *w/c*, the lower electrical resistivity (or higher conductivity) can be explained by a greater overall concentration of ions in solution, whereas for a higher *w/c*, the increased resistivity can be attributed to a less concentrated pore solution. In fact, as Wei and Li[14] have shown, the electrical resistivity of the pore solution increases with the *w/c*.* While some species with relatively low solubility (such as calcium hydroxide and gypsum) may quickly reach saturation for the whole range of *w/c* tested, other compounds (for example, potassium and sodium hydroxides) are highly soluble and will remain dissolved in different concentrations.[23] The pore solution concentrations of K+ and Na+ for a given *w/c* have been found to increase rapidly during the first 12 minutes after mixing but to remain nearly constant after that point up to approximately 3 hours.[24]

*Cement paste and concrete are significantly and inherently different materials, particularly when it comes to the effect of *w/c* on their bulk electrical resistivity in the fresh state. The direct relationship between electrical resistivity and *w/c*, observed for fresh concrete with a given consistency and for pore solution itself, is different than that verified for cement paste, in which resistivity is inversely related to *w/c*.[13] As mentioned previously—refer to Archie's law (Eq. (1)) and related discussion—in the case of fresh pastes with varying *w/c*, bulk resistivity is determined primarily by widely varying water content, not resistivity of pore fluid.

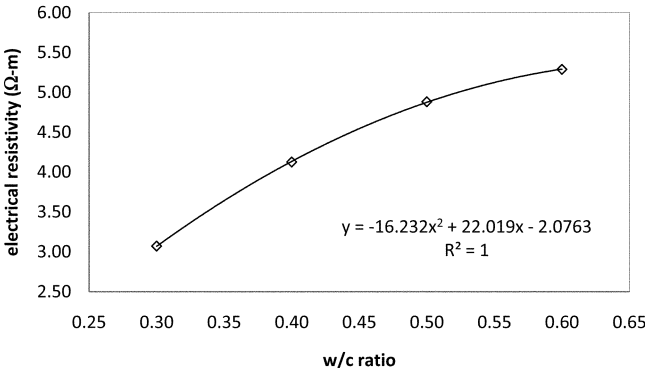

Fig. 5—Relationship between electrical resistivity and w/c *of fresh concrete (0% fly ash).*

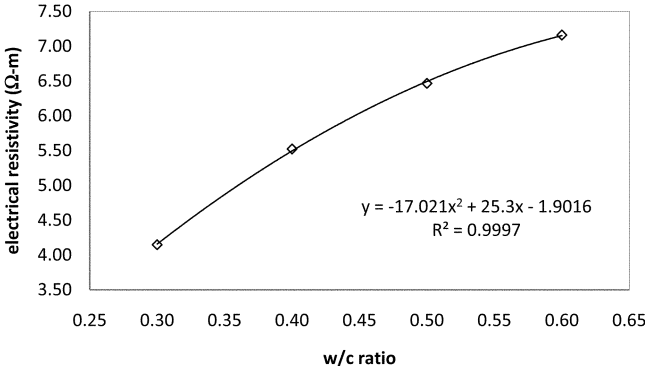

Fig. 6—Relationship between electrical resistivity and w/c *of fresh concrete (25% fly ash).*

It is important to point out that the characteristic resistivity measured for each concrete mixture is primarily a function of the resistivity of the pore fluid, rather than the amount of pore fluid. All fresh concrete mixtures tested had the same consistency and therefore approximately the same "porosity" (in the fresh, solution-saturated state, porosity equals water content plus entrapped air), so the quantity of pore fluid in each mixture was nearly constant. Therefore, any difference in the characteristic resistivity between samples must be attributed to the nature of the pore fluid, rather than the amount of pore fluid. Archie's law (Eq. (1)) provides further support for this assertion: the porosity volume fraction ϕ has been held constant; and, consequently, any changes in bulk resistivity ρ_b are caused solely by changes in the resistivity of the pore fluid ρ_f.

Statistical Analysis of Variance (ANOVA): influence of time and *w/c* on ρ

As shown in Table 5, in general, electrical resistivity increases with increasing *w/c*, but it remains relatively constant over time for early-age concrete. As mentioned previously, all experiments were conducted before initial setting of the cement. Replacing 25% of the concrete with fly ash increased the average resistivity by approximately 35% (likely a result of the slower dissolution rate of this material, which leads to a less concentrated and consequently more electrically resistant pore fluid), but the variation with *w/c* remained similar.

ANOVA tests were performed to identify the statistical significance of the variables investigated (time and *w/c*), as well as to quantify their effects. Two-factor, no replication

ANOVA tests were run on the resistivity measurements for all mixtures. The ANOVA test results are presented in Table 6, where *SS* is the sum of squares, *df* is degrees of freedom, and *MS* is mean squares (*MS* = *SS*/*df*). The term *F* is known as the Fisher parameter, which quantifies the degree to which variance in resistivity may be attributed to each factor analyzed. The *F*-ratio is the ratio between the variance of a parameter (in this case, resistivity) and the expected variance if the parameter and factor (in this case, time or *w*/*c*) are related. The greater this value, the greater the correlation between the parameter and the factor.[25] The *F*-critical value F_{crit} scales *F*; the greater the difference between *F* and F_{crit}, the more the parameter and factor are related. If $F > F_{crit}$, the factor exerts a statistically significant effect on the parameter. For those fresh concrete samples composed with either 0 or 25% fly ash, the calculated *F*-value for the *w*/*c* factor was much greater than the *F*-critical value, demonstrating that the *w*/*c* has a strong statistically significant effect on the resistivity of fresh concrete before initial setting. Conversely, because the calculated *F* value for the time factor was much less than the *F*-critical value for both concrete types, it can be said that time did not have a statistically significant effect on the measured resistivity values.

The *P*-value column expresses the probability that any correlation between the parameter and the factor (resistivity and time or *w*/*c*) is due solely to chance.[25] The high *P*-value for both types of concrete with respect to time suggests that the variation in resistivity is more likely to be due to chance or experimental error than related to time. Conversely, the low *P*-value for both types of concrete with respect to the *w*/*c* indicates that correlation between the *w*/*c* and resistivity is not due solely to chance.

The observation that resistivity appears to not vary significantly with time may be attributed to the fact that the formation of hydration products is incipient at this very early stage and has not yet considerably changed the overall concentration of ions in solution.

w/*c* estimates

A strong direct correlation was observed between electrical resistivity and the *w*/*c* of fresh concrete (Fig. 5 and 6). In this section, this correlation to estimate the *w*/*c* of concretes based on single, averaged resistivity measurements made with the resistivity probe described in this paper was used.

Resistivity readings from the probe were used as input in the fitted curves, and then the corresponding fitted quadratic equations (Fig. 5 and 6) were solved to obtain a *w*/*c* estimate (the equations are valid only between the upper and lower values of *w*/*c* tested). Table 7 presents the average *w*/*c* estimates obtained. The estimated values are virtually identical to the actual *w*/*c* values for all mixtures tested, with variations remaining smaller than 0.01. The error figures presented in this table are absolute values corresponding to estimates based on a single resistivity measurement made within the first 2 hours after mixing. In this case, the estimates show average errors of only 4.22% and 4.30%, for each concrete type, respectively (0 and 25% fly ash).

The small standard deviation and coefficient of variation further emphasize the limited error. Resistivity readings and individual *w*/*c* estimates were more accurate for mixtures with a *w*/*c* of less than 0.60, although average *w*/*c* estimates were satisfactory in all cases. This mixture (*w*/*c* = 0.60) contains a lower cement content and lower cohesiveness as compared to the lesser *w*/*c* mixtures, and it is possible that aggregate segregation (settling) occurred during the testing period, which could explain the variability in resistivity readings. In this case, it is important that mixing be continued until just before performing the resistivity readings.

Given that the relationship between *w*/*c* and compressive strength of concrete is usually known for a given mixture, a quick determination of the *w*/*c* in the field (based on the material's electrical resistivity) could also be used to estimate the expected compressive strength of that concrete.

Table 6(a)—ANOVA: effects of *w*/*c* and time on measured electrical resistivity of fresh concrete (0% fly ash)

ANOVA, 0% fly ash, 99% certainty						
Source of variation	*SS*	*df*	*MS*	*F*-value	*P*-value	*F*-critical
w/*c*	38.43	3	12.81	518.2	1.17×10^{-29}	4.377
Time	0.568	12	0.047	1.916	0.066	2.723
Error	0.890	36	0.025	—	—	—
Total	39.89	51	—	—	—	—

Table 6(b)—ANOVA: effects of *w*/*c* and time on measured electrical resistivity of fresh concrete (25% fly ash)

ANOVA, 25% fly ash, 99% certainty						
Source of variation	*SS*	*df*	*MS*	*F*-value	*P*-value	*F*-critical
w/*c*	66.56	3	22.19	349.2	1.17×10^{-26}	4.377
Time	0.439	12	0.037	0.575	0.847	2.723
Error	2.287	36	0.064	—	—	—
Total	69.29	51	—	—	—	—

Table 7(a)—Comparison between actual and estimated values of *w*/*c* (0% fly ash)

w/*c*, actual value	*w*/*c*, estimate	Standard deviation	Coefficient of variation, %	Average error, %	Maximum error, %	Minimum error, %
0.30	0.30	0.010	3.32	2.54	5.36	0.01
0.40	0.40	0.016	3.98	2.47	12.10	0.01
0.50	0.50	0.029	5.78	4.58	10.70	0.22
0.60	0.61	0.053	8.77	7.31	16.99	0.06

Notes: Estimates based on average resistivity values for each mixture. Errors refer to *w*/*c* estimates based on single measurements of ρ made during test period.

Table 7(b)—Comparison between actual and estimated values of *w*/*c* (25% fly ash)

w/*c*, actual value	*w*/*c*, estimate	Standard deviation	Coefficient of variation, %	Average error, %	Maximum error, %	Minimum error, %
0.30	0.30	0.006	1.93	1.52	3.60	0.01
0.40	0.40	0.017	4.10	2.90	8.39	0.03
0.50	0.50	0.024	4.79	3.71	10.24	0.31
0.60	0.60	0.065	10.78	9.05	17.54	3.04

Note: Estimates based on average resistivity values for each mixture. Errors refer to *w*/*c* estimates based on single measurements of ρ made during test period.

SUMMARY AND CONCLUSIONS

A simple probe was designed and constructed to instantaneously measure the electrical resistivity of fresh concrete, and thereby estimate the *w*/*c* of fresh concrete. Once the probe's geometric factor was determined, it was

used to conduct resistivity tests on a series of fresh concrete samples with different *w/c* (ranging from 0.30 to 0.60). The probe was vertically inserted into the center of a concrete sample held in a standard 6 x 12 in. (15 x 30 cm) plastic cylinder. A measurement can be obtained within a few milliseconds.

A relationship between resistivity and the *w/c* was established and tested, and two equations were developed to correlate the electrical resistivity of fresh concrete with its *w/c*. Results demonstrate that the method described herein can be used to accurately and instantaneously determine the *w/c* of fresh concrete based on the material's electric resistivity. The most significant findings are as follows:

1. There is a strong direct relationship between the *w/c* of fresh concrete and the material's electrical resistivity.

2. The use of fly ash tends to increase the electrical resistivity of fresh concrete.

3. Time did not have a statistically significant effect on the electrical resistivity of fresh concrete before initial setting.

4. The average *w/c* estimates based on the electrical resistivity of fresh concrete were virtually identical to the actual *w/c* values for all mixtures tested.

Practical application of the resistivity probe in the field should be preceded by a calibration of the relationship between *w/c* and electrical resistivity for the specific materials being used, similar to what is routinely done for the relationship between *w/c* and compressive strength of concrete. Future work may include the development of a battery-powered handheld unit that can internally calculate the electrical resistivity and display the corresponding *w/c* and compressive strength estimates. Mixtures containing chemical admixtures and higher volumes of mineral admixtures will also be studied. In addition, trials at actual job sites should be performed to test the efficiency of the proposed method and apparatus in field conditions.

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