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# INSTANTANEOUS *IN-SITU* DETERMINATION OF WATER-CEMENT RATIO OF FRESH CONCRETE

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## ABSTRACT

The water-to-cement (w/c) ratio 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 water-to-cement ratio. Experiments were conducted on eight concrete mixtures designed according to the ACI 211.1 procedure, with varying w/c ratios (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 water-to-cement ratio. Average w/c ratio estimates based on measurements using the resistivity probe were within  $\pm 0.01$  of the actual values for all mixtures tested.

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

## INTRODUCTION

1  
2 Instantaneous, *in-situ* measurement of the water-to-cement (w/c) ratio of fresh concrete is an  
3 unresolved challenge that has motivated engineers and researchers for several decades. A  
4 number of studies have explored various methods for determining the w/c ratio of concrete.  
5 The U.S. Army Construction Engineering Research Laboratory, for example, developed a  
6 technique based on chloride and calcium titration to determine, respectively, the water and  
7 cement contents of fresh concrete [1]. Popovics and Popovics (1998) explored applying  
8 ultrasonic pulses to both fresh and rapidly solidified concrete [2]. Other strategies have  
9 included separating the components of concrete: Bavelja (1970) developed a pressure-filter  
10 method of separating water from cement; Nägele and Hilsdorf (1980) attempted to separate  
11 cement by flotation; and Hime and Willis (1955) tried to separate cement using a centrifuge  
12 [1, 3-5]. The Kansas Department of Transportation (1994) continued Bavelja's work in  
13 pressure-sieving fresh concrete by using a turbidimeter to correlate the turbidity of the  
14 remaining solution to the w/c ratio [6]. The National Cooperative Highway Research Council  
15 (NCHRP) investigated applying solvents to determine w/c ratio and developed an acetone  
16 moisture content method [Hime, 1990]. The NCHRP also investigated the use of a specific  
17 ion electrode (bromide) to identify the presence of some common ions from cement [7], but  
18 the results were not promising.

19 A nuclear gage method developed in 1993 by Troxler Electronic Laboratories provided  
20 accurate results; however, only trained professionals can operate the nuclear device, which  
21 has limited the method's acceptance and widespread use [1, 8, 9]. In the microwave method,  
22 perhaps one of the most practical methods developed thus far, a sample of fresh concrete is  
23 weighed and then heated in a microwave oven to evaporate the water. The weight difference  
24 between the dry and wet samples, when combined with the cement proportion from the mix  
25 design, yields the water percentage and the w/c ratio [7, 10, 11]. The microwave test is a

1 relatively simple method, however, with limited application. It only measures the water  
2 content, takes between 15-30 minutes to dry a concrete sample, and safety concerns regarding  
3 the presence of metal in some aggregates remain an issue [12].

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

### 9 **Electrical resistivity and water-to-cement ratio of wet mixtures**

10 There have been two significant efforts to describe the w/c ratio of fresh cement paste and  
11 concrete mixtures from electrical resistivity measurements [9, 13]. Wei and Li [13] studied  
12 the early hydration process of Portland cement pastes using resistivity measurements  
13 conducted in a non-contacting device [14]. In their setup, cement paste was cast into a ring-  
14 shaped mold with a rectangular cross section, and an electrical current flow was induced in  
15 the specimen by an external transformer. Li's group characterized the bulk electrical  
16 resistivity of fresh cement pastes mixed with different w/c ratios, as well as the electrical  
17 resistivity of pore solutions extracted from the cement pastes by vacuum filtering. Based on  
18 their results, Wei and Li [13] suggested that electrical resistivity measurements can be used to  
19 determine the w/c ratio of fresh cement pastes; however, no experiments with concrete or  
20 mortar were performed. Their study provides valuable insight into the mechanisms of cement  
21 hydration, particularly regarding the dissolution of ions into solution and their relationship to  
22 electrical resistivity; however, the results have limited applicability when the electrical  
23 resistivity of concrete is considered.

24 Although cement paste (cement plus water) is an essential component of concrete, concrete is  
25 a composite material that necessarily includes aggregates (typically fine and coarse) and often

1 mineral and/or chemical admixtures. Cement paste and concrete have markedly different  
2 properties and behavior, both in the fresh (wet) and hardened states, primarily due to the  
3 presence of aggregates in concrete.

4 According to Archie's law, the bulk electrical resistivity of porous media is a function of two  
5 parameters: (1) resistivity of the pore fluid; and (2) porosity [15, 16]:

$$6 \quad \rho_b = \frac{\rho_f}{a\phi^m} \quad (1)$$

7 where  $\rho_b$  = bulk electrical resistivity,  $\rho_f$  = resistivity of the pore fluid,  $\phi$  = porosity (by  
8 volume), and  $a$  and  $m$  are empirical constants.

9 In fresh cement pastes (a solution-saturated porous media), porosity (or water content) varies  
10 significantly with the w/c ratio and has a strong influence on the bulk resistivity. In fresh  
11 concrete, as discussed in more detail below, fresh mixtures with different w/c ratios may have  
12 very similar "porosities" or overall water content [17]. In fact, according to ACI's standard  
13 concrete mix-proportioning procedure (ACI 211.1), for a given aggregate size and  
14 consistency (slump), different concrete mixes can have essentially the same overall water  
15 content (in lb/yd<sup>3</sup> [kg/m<sup>3</sup>]) independent of the w/c ratio, which is chosen based on the desired  
16 compressive strength [18, 24].

17 MacDonald and Northwood [9] attempted to characterize the relationship between the w/c  
18 ratio and electrical resistivity of fresh concrete. Samples for resistivity testing were prepared  
19 by sieving wet concrete through a #4 (4.75mm) screen, and resistivity measurements were  
20 conducted on the mortar fraction of concrete. After sieving, the wet mortar samples were cast  
21 into cylindrical molds and placed in a bench-top measuring circuit. Even though the  
22 aggregate size was kept constant in all mixes tested, the consistency (and consequently the  
23 water content) of the different mixes varied significantly. Careful analysis of their results  
24 reveals that the variation of electrical resistivity observed was primarily caused by changes in

1 porosity (which is approximately equal to water content in the fresh state), and *not* changes in  
2 the concrete's w/c ratio. Note that in construction practice, the slump of concrete (a measure  
3 of consistency) is specified based on the type of construction and the slump range is typically  
4 fixed for a given job [18]. The study by MacDonald and Northwood [9] also included an  
5 exploration of the diffusivity of chloride ions in concrete, and the authors ultimately  
6 concluded that it is possible to estimate the diffusivity of hardened concrete by measuring its  
7 resistivity. The researchers did not recommend electrical resistivity measurements as a means  
8 for estimating the w/c ratio of fresh concrete and noted that additional work would be  
9 required to develop a field procedure.

## 10 RESEARCH SIGNIFICANCE

11 Potential quality problems of a given concrete batch can usually be detected only after the  
12 material has hardened in the structure, when compressive strength experiments are performed.  
13 Remediation costs – including material, safety, labor, and time delays – can be substantial.  
14 Considering that existing methods for determining the w/c ratio of fresh concrete are  
15 cumbersome and often unreliable [19], new user-friendly and accurate techniques should be  
16 investigated. The objective of this research is to devise an efficient method and instrument to  
17 instantaneously determine the w/c ratio of fresh concrete in the field.

## 18 EXPERIMENTAL INVESTIGATION

### 19 Experimental setup

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

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

10 The current  $I_o$  passing through the circuit is given by  $V_o/R_o$ , and the electrical resistance of the  
11 concrete sample ( $R_c$ ) is equal to  $V_c/I_o$ . The electrical *resistivity* of the concrete ( $\rho_c$ ), a material  
12 property independent of sample geometry, is given by  $\rho_c = k.R_c$ , where  $k$  is the geometric  
13 factor (a parameter determined by the geometry of the probe used). As described later in  
14 more detail, the geometric factor for this resistivity probe immersed in solution has been  
15 analytically determined as  $k = 4\pi a$ , where  $a$  is the spacing between electrodes. Experimental  
16 verification of the calculated geometric factor was also carried out. To experimentally  
17 determine the value of this constant, the probe was submerged in aqueous solutions of known  
18 resistivities ( $\rho_s \approx 1 \Omega\text{-m}$ ,  $5 \Omega\text{-m}$ , and  $10 \Omega\text{-m}$ ), and the expression  $k = \rho_s/R_s$  was used to  
19 obtain the geometric factor. In this equation,  $R_s$  is given by  $V_s/I_o$ , i.e., the potential measured  
20 across the two inner electrodes divided by the current driven through the circuit.

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

22 In order to investigate the relationship between electrical resistivity and the w/c ratio of fresh  
23 concrete, eight samples with varying w/c ratios (0.30, 0.40, 0.50, and 0.60) and fly-ash  
24 percentages (0% and 25% of Type I/II cement replaced with Class F fly-ash) were prepared  
25 according to the ACI 211.1 mix design procedure [18]. Details of the concrete mixtures are

1 presented in Table 1. Note that because water content is a function of the desired workability  
2 and aggregate characteristics, concretes with the same slump but different w/c ratios typically  
3 have similar water content per unit volume. Based on the ACI procedure, a non-air-entrained  
4 concrete with maximum aggregate size of ½ in. [12.5 mm] and 3-4 in. [75-100 mm] slump,  
5 as used in this research, will have a mixing water content of about 365 lb/yd<sup>3</sup> [216 kg/m<sup>3</sup>]  
6 [18]. To avoid possible variations because of changes in tap-water resistivity, the initial  
7 resistivity of the mixing water was measured and kept constant at 80 Ω-m. Immediately after  
8 mixing, a portion of each concrete was poured into a 15 cm x 30 cm [6 in x 12 in] plastic  
9 cylinder to hold the sample as resistivity measurements were conducted over time. Standard  
10 for all measurements, the probe was vertically immersed in concrete and centrally-located  
11 within the plastic cylinder. Resistivity was measured at 10-minute intervals for about 2 hours,  
12 before initial setting of cement.

## 13 ANALYTICAL INVESTIGATION

### 14 Theoretical determination of the geometric factor (*k*)

15 The geometric factor for a Wenner electrode array in a homogeneous half space (as used in  
16 exploration geophysics and surface measurements in general) is known to be equal to  $2\pi a$  [16,  
17 20]. In our application, however, the resistivity probe is completely immersed in the  
18 surrounding medium. As current flows through the circuit and the concrete from electrode A  
19 to B (see Figure 2b), electrode A can be thought of as a point source of current in a spherical  
20 whole space, as illustrated in Figure 3. The current  $I$  flowing through this sphere can be  
21 expressed as

$$22 \quad I = J \cdot 4\pi r^2 \quad (2)$$

23 where  $J$  is current density and  $4\pi r^2$  is the surface area of the spherical whole space. Because  
24 electrical conductivity ( $\sigma = I/\rho$ ) is defined as the ratio between current density ( $J$ ) and



1 electric field ( $E$ ), and considering that the electric field at a point is equal to the negative  
 2 gradient of the electric potential ( $\phi$ ), the expression above can be rewritten as

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

4 In this equation,  $\phi$  is a scalar quantity representing the electric potential at a single point.  
 5 Expressing the electric potential gradient in spherical coordinates ( $\nabla\phi = d\phi/dr$ ) and  
 6 integrating the resulting expression, the electric potential at a point on the spherical surface  
 7 ( $\phi$ ) can be expressed as a function of the current ( $I$ ), resistivity ( $\rho$ ), and radius of the whole  
 8 space ( $r$ ):

$$9 \quad \phi = \frac{I}{\sigma \cdot 4\pi r} + C = \frac{I \cdot \rho}{4\pi r} + C \quad (4)$$

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

$$17 \quad \phi_M = \frac{I_A \rho}{4\pi a} - \frac{I_B \rho}{4\pi(2a)} \quad (5)$$

18 Similarly, the potential at electrode N is

$$19 \quad \phi_N = \frac{I_A \rho}{4\pi(2a)} - \frac{I_B \rho}{4\pi(a)} \quad (6)$$

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

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

Solving this expression for resistivity ( $\rho$ ), we find

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

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 next section, the calculated geometric factor  $k$  for our probe, which equals 0.319 ( $a = 1 \text{ in.} = 0.0254 \text{ m}$ ), was very similar to the experimental value (less than 2.5% difference).

## RESULTS AND DISCUSSION

### Experimental determination of the geometric factor ( $k$ )

The empirical determination of the probe's geometric factor was based on eighteen measurements conducted with aqueous solutions of low, medium, and high electrical resistivity (see Table 2). The average measured value for  $k$  was 0.327, which is only 2.5% higher than the theoretical value calculated above. 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.

Both calibration and concrete resistivity measurements were obtained by vertically embedding the probe in the center of the sample, which was the standard 15 cm x 30 cm [6 in x 12 in] plastic cylinders typically used for compressive strength testing. Measurements

1 taken off-center and close to the cylinder wall are influenced by the difference in  
2 conductivities between the concrete and the plastic container and should be avoided.  
3 It is worth noting the geometric factor ( $k$ ) is a constant that depends solely on the geometry of  
4 the resistivity apparatus, and needs to be determined only once, at the product development  
5 stage.

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

7 Resistivity measurements were made at 10-minute intervals for each of the eight different  
8 samples during the first two hours after mixing. Two measurements were made at each time  
9 interval, and average values for each mix were calculated including all readings made during  
10 the testing period. All measurements were made using the probe apparatus described above.  
11 Tables 3 and 4 present the average resistivity values measured as a function of w/c ratio for  
12 each of the mixes, while Figures 5 and 6 illustrate the relationship between the w/c ratio and  
13 electrical resistivity of fresh concrete. As expected, the electrical resistivity of fresh concrete  
14 increased with increasing w/c ratio (quite differently than occurs with hardened concrete). At  
15 a lower w/c ratio, the lower electrical resistivity (or higher conductivity) can be explained by  
16 a greater overall concentration of ions in solution, while for a higher w/c ratio, the increased  
17 resistivity can be attributed to a less concentrated pore solution. In fact, as Wei and Li [13]  
18 have shown, the electrical resistivity *of the pore solution* increases with the w/c ratio<sup>1</sup>. While  
19 some species with relatively low solubility (such as calcium hydroxide and gypsum) may  
20 quickly reach saturation for the whole range of w/c ratios tested, other compounds (e.g.,  
21 potassium and sodium hydroxides) are highly soluble and will remain dissolved in different

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

1 concentrations [21]. The pore solution concentrations of  $K^+$  and  $Na^+$  for a given w/c ratio  
2 have been found to increase rapidly during the first 12 minutes after mixing but to remain  
3 nearly constant after that point up to about 3 hours [22].  
4 It is important to point out that the characteristic resistivity measured for each concrete mix is  
5 primarily a function of the resistivity of the pore fluid, rather than the amount of pore fluid.  
6 All fresh concrete mixes tested had the same consistency and therefore approximately the  
7 same “porosity” (in the fresh, solution-saturated state, porosity equals water content plus  
8 entrapped air), so the quantity of pore fluid in each mix was nearly constant. Therefore, any  
9 difference in the characteristic resistivity between samples must be attributed to the nature of  
10 the pore fluid, rather than the amount of pore fluid. Archie’s law (Equation 1) provides  
11 further support for this assertion: the porosity volume fraction ( $\phi$ ) has been held constant, and,  
12 consequently, any changes in bulk resistivity ( $\rho_b$ ) are caused solely by changes in the  
13 resistivity of the pore fluid ( $\rho_f$ ).

#### 14 **Statistical Analysis of Variance (ANOVA): influence of time and w/c on $\rho$**

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

22 Analysis of Variance (ANOVA) tests were performed to identify the statistical significance  
23 of the variables investigated (time and w/c ratio), as well as to quantify their effects. Two-  
24 factor, no replication ANOVA tests were run on the resistivity measurements for all mixes.

1 The ANOVA test results are presented in Table 6, where  $SS$  signifies “sum of squares,”  $df$   
2 denotes “degrees of freedom,” and  $MS$  indicates “mean squares” ( $MS = SS/df$ ). The term  $F$  is  
3 known as the Fisher parameter, which quantifies the degree to which variance in resistivity  
4 may be attributed to each factor analyzed. The  $F$ -ratio is the ratio between the variance of a  
5 parameter (in this case, resistivity) and the expected variance if the parameter and factor (in  
6 this case, time or w/c ratio) are related. The greater this value, the greater the correlation  
7 between the parameter and the factor [23]. The  $F$ -critical value ( $F_{crit}$ ) scales  $F$ ; the greater the  
8 difference between  $F$  and  $F_{crit}$ , the more the parameter and factor are related. If  $F > F_{crit}$  the  
9 factor exerts a statistically significant effect on the parameter. For those fresh concrete  
10 samples composed with either 0% or 25% fly-ash, the calculated  $F$ -value for the w/c ratio  
11 factor was much greater than the  $F$ -critical value, demonstrating that the w/c ratio has a  
12 strong statistically significant effect on the resistivity of fresh concrete before initial setting.  
13 Conversely, since the calculated  $F$  value for the time factor was much less than the  $F$ -critical  
14 value for both concrete types, it can be said that time did not have a statistically significant  
15 effect on the measured resistivity values.

16 The “ $P$ -value” column expresses the probability that any correlation between the parameter  
17 and the factor (resistivity and time or w/c ratio) is due solely to chance [23]. The high  $P$ -value  
18 for both types of concrete with respect to time suggests that the variation in resistivity is more  
19 likely to be due to chance or experimental error than related to time. Conversely, the low  $P$ -  
20 value for both types of concrete with respect to the w/c ratio indicates that correlation  
21 between the w/c ratio and resistivity is not due solely to chance.

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

## 25 **Water-to-cement ratio estimates**

1 A strong direct correlation was observed between electrical resistivity and the w/c ratio of  
2 fresh concrete (Figures 5 and 6). In this section, we use this correlation to estimate the w/c  
3 ratio of concretes based on single, averaged resistivity measurements made with the  
4 resistivity probe described in this paper.

5 Resistivity readings from the probe are used as input in the fitted curves, and then the  
6 corresponding fitted quadratic equations (Figures 5 and 6) are solved to obtain a w/c ratio  
7 estimate (the equations are valid only between the upper and lower values of w/c ratio tested).  
8 Table 7 presents the average w/c ratio estimates obtained. The estimated values are virtually  
9 identical to the actual w/c values for all mixes tested, with variations remaining smaller than  
10 0.01. The error figures presented in this table are absolute values corresponding to *estimates*  
11 *based on a single resistivity measurement* made within the first two hours after mixing. In  
12 this case, the estimates show average errors of only 4.22% and 4.30%, for each concrete type,  
13 respectively (0% and 25% fly-ash).

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

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

## 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 ratio 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 ratios (ranging from 0.30 to 0.60). The probe was vertically inserted into the center of a concrete sample held in a standard 6 in x 12 in [15 cm x 30 cm] plastic cylinder. A measurement can be obtained within a few milliseconds.

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

- there is a strong direct relationship between w/c ratio of fresh concrete and the material's electrical resistivity,
- the use of fly ash tends to increase the electrical resistivity of fresh concrete,
- time did not have a statistically significant effect on the electrical resistivity of fresh concrete before initial setting, and
- average w/c ratio estimates based on the electrical resistivity of fresh concrete were virtually identical to the actual w/c values for all mixes tested.

Practical application of the resistivity probe in the field should be preceded by a calibration of the relationship between w/c ratio and electrical resistivity for the specific materials being used, similarly to what is routinely done for the relationship between w/c ratio 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 ratio and compressive strength estimates. Mixtures containing chemical

- 1 admixtures and higher volumes of mineral admixtures will also be studied. In addition, trials
- 2 at actual jobsites should be performed in order to test the efficiency of the proposed method
- 3 and apparatus in field conditions.



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Table 1 – Concrete mix proportions (FA= fine aggregate, CA = coarse aggregate). Specific gravity of materials: cement = 3.15, fly ash = 2.60, FA = 2.67, CA = 2.68.

Mix #	w/c ratio	Unit proportions				Amounts (SSD), kg/m <sup>3</sup> [lb/yd <sup>3</sup> ]				
		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]

Table 2 – Empirical determination of the probe's average geometric factor (*k*)

Solution type	#	$\rho$ ( $\Omega$ -m)	<i>k</i> 1	<i>k</i> 2
Low $\rho$ ( $\approx 1 \Omega$ -m)	1	0.93	0.315	0.313
	2	0.98	0.351	0.351
	3	0.90	0.360	0.361
Medium $\rho$ ( $\approx 5 \Omega$ -m)	4	4.55	0.303	0.304
	5	4.55	0.290	0.291
	6	4.50	0.334	0.335
High $\rho$ ( $\approx 10 \Omega$ -m)	7	9.35	0.330	0.296
	8	9.52	0.330	0.342
	9	9.90	0.336	0.335
Average geom. factor =			<b>0.327</b>	
Standard deviation =			<b>0.023</b>	

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

w/c	Avg. $\rho$ ( $\Omega$ -m)	Standard deviation	Coeff. 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	Avg. $\rho$ ( $\Omega$ -m)	Standard deviation	Coeff. of variation
<b>0.30</b>	4.15	0.087	2.10%
<b>0.40</b>	5.52	0.192	3.30%
<b>0.50</b>	6.47	0.203	3.07%
<b>0.60</b>	7.16	0.415	6.41%

Table 5 – Electrical resistivity of concrete as a function of time and w/c ratio

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

Table 6 – Analysis of Variance (ANOVA): effects of w/c ratio and time on the measured electrical resistivity of fresh concrete. (a) 0% fly ash, (b) 25% fly ash

<b>ANOVA, 0% fly ash, 99% certainty</b>						
Source of variation	SS	df	MS	F value	P value	F critical
<b>W/C ratio</b>	38.43	3	12.81	<b>518.2</b>	1.17E-29	<b>4.377</b>
<b>Time</b>	0.568	12	0.047	1.916	0.066	2.723
Error	0.890	36	0.025			
Total	39.89	51				

(a)

<b>ANOVA, 25% fly ash, 99% certainty</b>						
Source of variation	SS	df	MS	F value	P value	F critical
<b>W/C ratio</b>	66.56	3	22.19	<b>349.2</b>	1.17E-26	<b>4.377</b>
<b>Time</b>	0.439	12	0.037	0.575	0.847	2.723
Error	2.287	36	0.064			
Total	69.29	51				

(b)

Table 7 – Comparison between actual and estimated values of the w/c ratio: (a) 0% fly ash, and (b) 25% fly ash. Estimates are based on average resistivity values for each mix. Errors refer to w/c estimates based on single measurements of  $\rho$  made during the test period.

w/c ratio (actual value)	w/c ratio (estimate)	Standard deviation	Coeff. of variation	Avg. error	Max. error	Min. error
<b>0.30</b>	<b>0.30</b>	0.010	3.32%	2.54%	5.36%	0.01%
<b>0.40</b>	<b>0.40</b>	0.016	3.98%	2.47%	12.10%	0.01%
<b>0.50</b>	<b>0.50</b>	0.029	5.78%	4.58%	10.70%	0.22%
<b>0.60</b>	<b>0.61</b>	0.053	8.77%	7.31%	16.99%	0.06%

(a)

w/c ratio (actual value)	w/c ratio (estimate)	Standard deviation	Coeff. of variation	Avg. error	Max. error	Min. error
<b>0.30</b>	<b>0.30</b>	0.006	1.93%	1.52%	3.60%	0.01%
<b>0.40</b>	<b>0.40</b>	0.017	4.10%	2.90%	8.39%	0.03%
<b>0.50</b>	<b>0.50</b>	0.024	4.79%	3.71%	10.24%	0.31%
<b>0.60</b>	<b>0.60</b>	0.065	10.78%	9.05%	17.54%	3.04%

(b)



Fig. 1 – Electrical resistivity probe developed in this study. Electrode spacing is 2.5 cm [1 in].

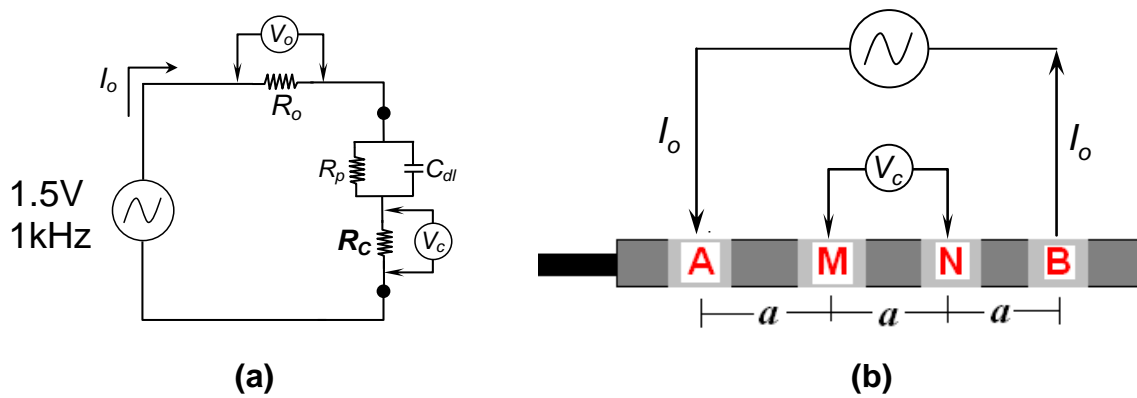


Fig. 2 – Schematic illustrations of (a) the electric circuit; and (b) resistivity probe

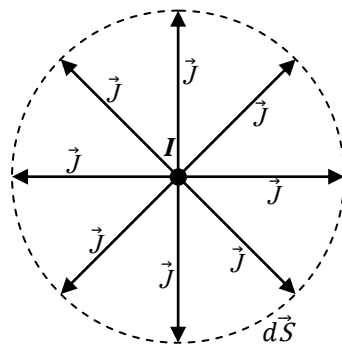


Fig. 3 – Point source of current ( $I$ ) in a spherical whole space

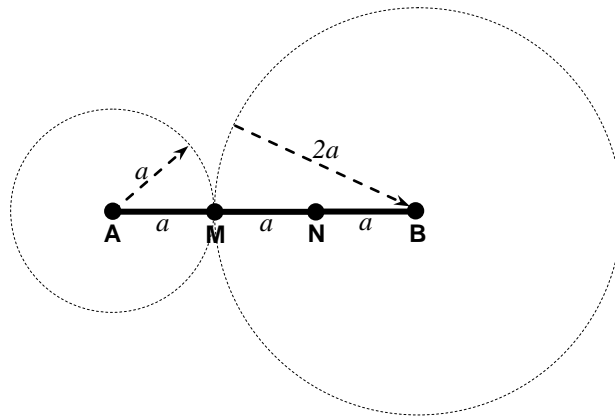


Fig. 4 – The electric potential measured at the inner electrode M is determined by the difference between single-point potentials at outer electrodes A and B

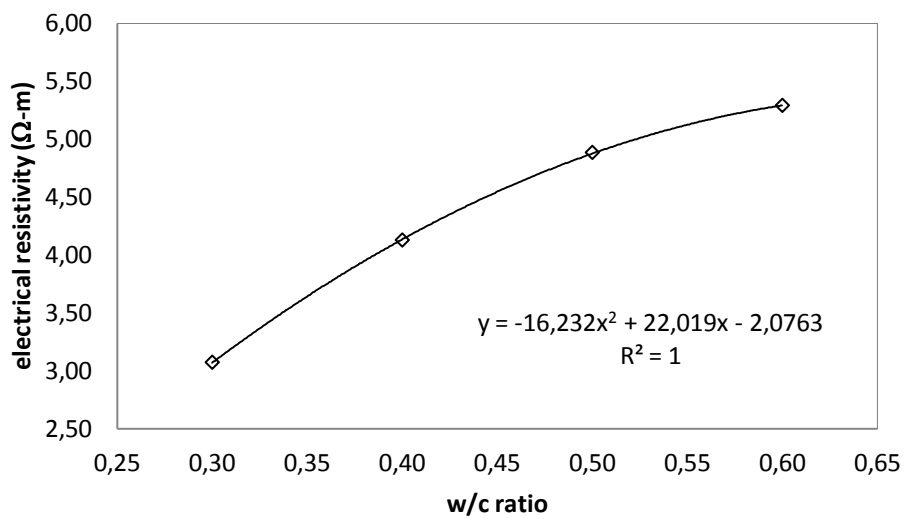


Fig. 5 – Relationship between electrical resistivity and w/c ratio of fresh concrete (0% fly ash)



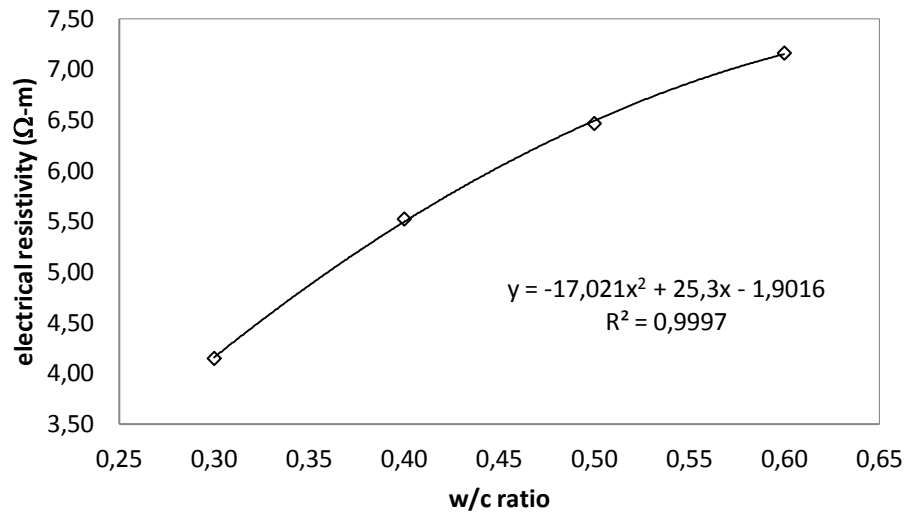


Fig. 6 – Relationship between electrical resistivity and w/cm ratio of fresh concrete (25% fly ash)