Evaluation of ASTM Standard Practice on Measuring the Electrical Resistance of Fresh Concrete

FINAL REPORT

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Introduction

A new standard practice on Measuring the Electrical Resistance of Fresh Concrete has been proposed at ASTM. The practice describes procedures for sampling and measuring the resistance of fresh concrete during setting and subsequent hardening under sealed curing conditions in the laboratory or in the field. Electrical resistivity of concrete is an intrinsic material property that measures the speed at which ions in pore solution move through concrete under an applied electric field. Factors that impact resistivity are the pore volume – related to water content; pore structure – size and connectivity; conductivity of pore solution – related to ionic concentration; degree of saturation of the specimen; and specimen temperature. In this practice, electrical resistance is measured and is a function of the specimen geometry. Some of these impacts of porosity are applicable to hardened concrete and may not be as significant for fresh concrete. An alternating current (AC) 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. The practice provides guidance on converting measured resistance to resistivity. It suggests that either resistance measured for a fixed geometry or the calculated resistivity can provide a signature of a specific concrete mixture and can be part of a quality control program.

The scope of the practice indicates that the measured resistance of concrete can be used to estimate the water-to-cementitious materials ratio (*w/cm*) of concrete delivered to a project site. This estimate would be based on a pre-established correlation for a specific concrete mixture with consideration of the concrete temperature. It also states that the measured resistance can be used to anticipate setting time of concrete by evaluating the change in measured resistance as a function of time. This estimate would also require a pre-established relationship between resistance and setting times measured with the same materials and mixture proportions in the laboratory. The practice cautions that the same electrode configuration operating at the same alternating current (AC) frequency should be used for comparisons.

Objective

The objectives of this limited study are as follows:

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

   The findings will help determine which alternative is more sensitive to a change in resistance. The practice allows both options.
2. Measure change in resistance with time
    - This will provide background on how to interpret field data vs. lab data. Field resistance will typically be measured in the time frame of 45 to 90 minutes after mixing, while lab data is measured immediately after mixing.
3. Investigate the impact of the following variables of concrete mixtures at the same *w/cm* on measured resistance:
    - Change in paste volume
    - Use of 25% fly ash in the mixture
    - Variation of alkali content of portland cement
    - Use of common admixtures like HRWRA
    - Air entrainment

4. Develop single operator precision information.

The wireless device used in this study for the measurement of electrical resistance is shown in Figure 1. The resistance is measured on a 4x8 in. cylindrical specimen of freshly mixed concrete. In this study the specimen shape and size were kept the same. The impact of temperature was not evaluated.

Interpreting Measured Resistance for Estimating the w/cm in Concrete

Using the NIST model[1] and assuming no cement hydration, the estimated pore solution conductivity of fresh concrete for a low alkali portland cement mixture with 0.37, 0.42, and 0.47 *w/cm* are 6.71, 6.01, and 5.42 S/m respectively. The NIST model assumes that 75 % of the total alkalis are readily soluble and as the *w/cm* is increased the ionic concentration in the pore solution will decrease leading to a reduction in pore solution conductivity. In a concrete mixture, an increase in w/cm will lead to an increase in resistivity and this is referred to as the "pore solution" effect in the discussion below.

In concrete mixtures, increasing *w/cm* can be accomplished by maintaining the same paste volume, or by increasing or decreasing the paste volume. The following are possible impacts of increasing *w/cm* on the measured resistance of fresh concrete:

- At a constant paste volume, increasing w/cm increases the mixing water content and reduces the cementitious content. The higher mixing water content will provide greater pathways for the ions which will lower the resistivity of the fresh concrete. At the same time, the "pore solution" effect will lead to an increase in resistivity. As a result of these competing effects, as w/cm is increased, the measured resistance may increase or decrease depending on which of the factors is controlling.
- Increasing w/cm by using higher mixing water content while maintaining the same cementitious content increases the paste volume. The increase in mixing water content will be greater than in the constant paste volume case. The higher mixing water content will provide greater pathways for the ions which will lower the resistivity of the fresh concrete. At the same time, the "pore solution" effect will lead to an increase in resistivity. Even though these are competing effects, as w/cm is increased the measured resistance is likely to decrease.
- Increasing *w/cm* by reducing cementitious content at the same mixing water content decreases paste volume. As *w/cm* is increased, due to the "pore solution" effect the measured resistance will increase. Mancio et al. reported increasing resistance with increasing *w/cm*. In their study, they varied the *w/cm* by varying the cementitious content while keeping the mixing water content constant. So, increase in *w/cm* resulted in mixtures with lower paste volumes.

The above discussion suggests that when developing a correlation between *w/cm* and resistance in the laboratory, it would be more appropriate to vary the paste volume when varying *w/cm*. In ready mixed concrete production, for a specific mixture, the quantity of cementitious materials batched would be essentially controlled and constant and the mixing water content would vary thereby causing a variation of the paste volume. A correlation of *w/cm* vs resistance should be developed by varying water content while maintaining a constant cementitious materials content. This would represent the more realistic situation and allow one to better predict the *w/cm* of concrete delivered to projects based on electrical measurements.

Experimental Factors

Table 1 shows the concrete mixtures evaluated in this study. A low alkali cement with an equivalent alkali content of 0.48% was used for all of the mixtures except Mixture 8.

- In Mixtures 1, 2, and 3 the *w/cm* was varied as 0.37, 0.42, and 0.47, respectively. The quantity of portland cement content was maintained constant and the mixing water content was varied. The resulting paste volumes of these mixtures was determined to be 26%, 28% and 30%, respectively. The paste volume is calculated as the sum of the volumes of the cementitious materials and the mixing water content expressed as a percent of the concrete volume.
- In mixtures 2, 4, and 5 the *w/cm* was varied as 0.37, 0.42, and 0.47, respectively by maintaining the same paste volume of 28.5% and changing the proportion of water to cement.
- Mixture 6 had the same *w/cm* (0.47) as Mixture 3 but was proportioned at a lower paste volume (24.8% vs 30.4%). The fine aggregate quantity was adjusted to compensate for change in paste volume.
- Mixture 7 included 25% fly ash by volume of cementitious materials with the same *w/cm* (0.42) and paste volume (28.5%) as Mixture 2.
- Mixture 8 had the same *w/cm* (0.42) and paste volume (28.5%) as Mixture 2 but contained a high alkali cement with an equivalent alkali content of 0.90%.
- Mixture 9 had the same *w/cm* (0.47) and paste volume (30.4%) as Mixture 3 but the high range water reducing admixture was not used in this mixture.
- Mixture 10 is an air entrained mixture with the same *w/cm* (0.42) and paste volume (28.5%) as Mixture 2.

The following procedures were used on Mixtures 1-3. The purpose was to obtain information on single laboratory repeatability of resistance measurements and to evaluate the impact of time. After the concrete was mixed, a sample of concrete was obtained while retaining the remaining concrete in the mixer. Properties measured include slump, air content, temperature, density, and two 4x8 in. cylinders were prepared for measuring compressive strength at 42 days.
Six 4x8 in. concrete cylinders were prepared for the resistance measurements. The resistance measurements were made on each cylinder by two operators using two sets of devices resulting in 12 resistance measurements for each mixture. The operators interchanged cylinders for measurements. One cylinder was left connected to obtain a resistance measurement at 90 min. The concrete left in the mixer was mixed for 1 minute every 5 min until about 90 min. This was done to simulate the time and mixing of delivering ready mixed concrete. A sample was obtained at 90 min from which three cylinders were prepared for resistance measurements.
For mixtures 4-10, three 4x8 in. concrete cylinders were prepared for the resistance measurements. The resistance was measured by one operator.
For all the mixtures, slump varied between 2 and 9 in. HRWR admixture dosages were used to keep the slump within that range. All mixtures were non-air-entrained with the exception of Mixture 10.

Experimental Results

Concrete mixture proportions and test results are shown in Table 2. The resistance measurements of Mixtures 1-3 are an average of 12 readings while the resistance measurements on Mixtures 4-10 are an average of 3 readings. Since Mixture 4 had been in cast with an incorrect *w/cm* (0.39) Mixture 4R had to be cast with the correct *w/cm* of 0.37. Mixture 1R was a replicate of Mixture 1 to evaluate the batch effect on resistance measurements. The following observations can be made.

1. Figure 2 shows a correlation between measured resistance and *w/cm* for Mixtures 1, 2, and 3. For these mixtures the *w/cm* was decreased by decreasing mixer water content while maintaining a constant cement content. The lower mixing water content resulted in fewer pathways for the

transport of the charged ions and therefore increased resistance. Reduction in *w/cm* resulted in a small increase in measured resistance. The measured resistance increased by about 18% when *w/cm* was decreased from 0.47 to 0.37.

2. Figure 3 shows the 42-d strength vs *w/cm* for Mixtures 1, 2, and 3. As the *w/cm* decreased, the strength increased. The impact of changing *w/cm* on strength is more significant than the change in measured resistance as can be observed by the slopes of the lines in Figure 2 and 3. The increase in strength is about 51% when *w/cm* is decreased from 0.47 to 0.37.
3. Figure 4 shows a correlation between measured resistance and *w/cm* for Mixtures 4R, 4, 2, and 5. Since paste volume is kept constant, as the *w/cm* decreased, the water content decreased, while cement content increased. This resulted in fewer pathways for more charged ions. These two opposing factors resulted in only a small increase in the measured resistance as *w/cm* was increased. The measured resistance was not sensitive to a change in w/c*m* for these mixtures. This suggests when developing a laboratory correlation for resistance to *w/cm*, maintaining a constant paste volume is less predictive than a relationship where the paste volume is varied (Figure 2).
4. Figure 5 shows the strength vs *w/cm* for Mixtures 4R, 4, 2, and 5. As expected as the *w/cm* decreased, the strength increased. Strength is a better predictor of *w/cm* than measured resistance for these mixtures.
5. Mixture 6 had the same *w/cm* (0.47) as Mixture 3 but a lower paste volume (24.6% vs 30.4%). The lower paste volume resulted in 42% higher measured resistance as the lower cement content contributed less charged ions to the pore solution while the lower mixing water provided fewer pathways for the ions.
6. Figure 6 shows the inverse of resistance for all the mixtures containing low alkali cement plotted against the volume of cement or 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, however, the sum of cement and water volumes correlated better with the measured resistance.
7. Mixture 7 had the same *w/cm* and paste volume as Mixture 2 with the difference that Mixture 7 included 25% fly ash by volume of cementitious materials. The fly ash mixture had a 25% higher measured resistance. The NIST model predicts after initial mixing the portland cement mixture had 25% higher pore solution conductivity than the fly ash mixture. The water content was nearly identical in the two mixtures. It is likely that the measured resistance in these mixtures is impacted by the relative ionic concentration in the pore solution. With the dilution of portland cement, it is likely that the ions in solution in the fly ash mixture is less than that of the portland cement mixture. This likely resulted in a higher measured resistance for the fly ash concrete mixture.
8. Mixture 8 had the same *w/cm* and paste volume as Mixture 2 but with a high alkali portland cement as compared to the low alkali cement (Mixture 2). The high alkali cement mixture resulted in a 35% lower measured resistance. The NIST model predicts that after initial mixing the high alkali cement mixture would have a 43% lower pore solution resistivity than the low alkali cement mixture, assuming the same percentage of readily soluble alkalis relative to total alkalis for both cements.
9. Mixture 9 had the same *w/cm* (0.47) and paste volume (30.4%) as Mixture 3 but had no high range water reducing admixture. The use of this HRWR admixture at the dosages (0 vs 2.5 oz/cwt.) used here does not seem to influence the measured resistance.
10. Mixture 10 was air-entrained at the same *w/cm* (0.42) and paste volume (28.5%) as the non-air-entrained Mixture 2. The air content was 4.2% for Mixture 10 compared to 2.5% for Mixture 2. The entrained air did not seem to influence the measured resistance.
11. Readings after 90 min of simulated mixing are slightly higher than readings taken at 90 min on initially cast specimens. There seems to be an effect of *w/cm*. Mixture 1 with 0.37 *w/cm* showed

that the simulated mixing resulted in about 16% higher measured resistance; Mixture 2 with 0.42 *w/cm* showed that the simulated mixing resulted in about 6% higher measured resistance; Mixture 3 with 0.47 *w/cm* showed that the measured resistance after the simulated mixing period was the same. It appears that simulated mixing might be changing the pore solution concentration of lower *w/cm* mixtures (particularly those below 0.42) resulting in an increase in measured resistance.

12. For the batch to batch repeatability evaluation, Mixture 1R had a higher average measured resistance (4.4 ohms) than Mixture 1. The difference in the range of individual measurement between Mixture 1 and 1R is higher (8 ohms). The measured strength of 1R is lower than Mixture 1 suggesting 1R might have had a slightly higher *w/cm*. Figure 3 suggests that *w/cm* of Mixture 1R is likely to have been about 0.40. However, if Mixture 1R had higher w/cm than Mixture 1 it should have resulted in a lower measured resistance (from Figure 1) than Mixture 1. This suggests that batch to batch variation may have to be investigated as it is likely to have a greater impact than within batch variation.
13. The data from Mixtures 4-10 show that a range of measured resistance of about 3 ohms is common when 3 specimens are tested from same concrete mixture. Figure 7 shows the resistance vs *w/cm* for Mixtures 1, 2, and 3. The range of 12 measured values from six specimens for each mixture is also shown. The individual measurements for resistance values for the 0.37 and 0.42 mixtures overlap suggesting that the variation in resistance measurements are not discerning enough to distinguish between mixtures where the *w/cm* differs by 0.05. With mixtures at the same paste volume (Mixtures 2, 4, 4R, and 5) resistance measurements are not discerning enough to distinguish between mixtures where the *w/cm* differs by 0.10.
14. The single operator standard deviation for the resistance test was determined to be 1.42 ohms. The single-operator coefficient of variation was 3.85%. The average resistance of the mixtures evaluated varied between 24 and 47 ohms. 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 ohms or 10.8% of the average in more than 95% of the cases. Going by the precision statement of the slump test and the specified tolerances for slump in ASTM C94, it seems appropriate to suggest a tolerance of ±4 ohms to the specified value if this test were to be used as an acceptance test. ASTM D6607 can be used to determine rational measurement tolerances after considering the precision of the test method and quantified material variation. If the material variation is of the same magnitude as the precision of the test method, the effective standard deviation can be calculated as 2 ohms. For a 2-ended measurement, tolerance at 95% confidence level can be suggested as ±3.9 ohms. It is interesting to note that the suggested measurement tolerances arrived at ASTM D6607 matches very closely with that arrived at after comparisons with the tolerance used for the slump test. Figure 8 shows the suggested measurement tolerances for resistance as an indicator for w/cm overlaid on average data from Mixtures 1, 2, and 3. The considerable overlap shows that it is very hard to distinguish between 0.37 and 0.47 w/cm concrete mixtures using a single resistance measurement.
15. It is important to note that the single operator coefficient of variation of this test (3.85%) is only slightly higher than that of the ASTM C39 compressive strength test (3.2%). However, the main reason why resistance does not appear to be a good indicator for *w/cm* is that the resistance values measured for the 3 w/cm mixtures are not significantly different compared to the differences in the compressive strength of the mixtures. As the *w/cm* was decreased from 0.47 to 0.37 the strength increased by 51% while the resistance increased by only 18%. If the resistance test is calculated from an average of 3 resistance measurements (3 specimens made from the same sample of concrete in a wheelbarrow) the single operator standard deviation for the resistance test can be calculated as 0.82 ohms and measurement tolerances for 95% confidence

level can be calculated as ±3.2 ohm. This would make it easier to distinguish between 0.37 and 0.47 w/cm concrete mixtures. This type of variation would need to be further evaluated in truck mixed concrete under project conditions, if this practice proposes to use resistance of fresh concrete as an acceptance method to discern *w/cm* of concrete on projects.

References

1. Estimation of Pore Solution Conductivity, https://www.nist.gov/el/materials-and-structural-systems-division-73100/inorganic-materials-group-73103/estimation-pore
2. Mancio M., Moore, J.R., Brooks, Z., Monteiro, P.J.M., and Glaser, S.D., 2010, "Instantaneous In-Situ Determination of Water-Cement Ratio of Fresh Concrete", ACI Materials Journal, V. 107, No. 6, November-December 2010, PP. 587-593.

Table 1 Proposed Mixtures Proportions (lbs/yd3)

Mixture No.	1	2	3	4	5	6	7	8	9	10
Low Alkali Cement	650	650	650	697	609	530	500		650	650
High Alkali Cement								650		
Fly Ash							138			
Water	241	273	306	258	286	249	268	273	306	273
Air, %	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	6.0
HRWRA, oz/cwt	8.50	4.30	2.40	6.50	4.00	5.00	4.00	4.50	0.00	3.00
w/cm	0.37	0.42	0.47	0.37	0.47	0.47	0.42	0.42	0.47	0.42
Paste Volume (W+CM)	0.265	0.285	0.304	0.285	0.285	0.248	0.285	0.285	0.304	0.285

Table 2 Mix Proportions and Test Results

Mixture ID	1	1R	2	3	4	4R	5	6	7	8	9	10
Yield Adjusted Proportions												
Total Cementitious	638	645	648	649	693	704	606	527	641	648	651	663
Low Alkali Portland Cement, lb/yd^3	638	645	648	649	693	704	606	527	503		651	663
High Alkali Portland Cement, lb/yd^3										648		
Fly Ash, lb/yd^3									138			
Coarse Agg. (No.57), lb/yd^3	1807	1827	1836	1840	1831	1859	1834	1830	1852	1836	1843	1879
Fine Aggregate, lb/yd^3	1532	1515	1437	1355	1434	1456	1436	1594	1437	1437	1358	1291
Mixing Water, lb/yd^3	237	238	272	305	267	260	285	247	269	272	306	278
HRWRA, oz/cwt	8.65	8.50	4.30	2.48	6.50	8.50	1.87	5.00	5.09	4.50	0.00	3.00
w/cm	0.3713	0.37	0.42	0.47	0.3849	0.37	0.47	0.47	0.42	0.42	0.47	0.42
Paste Volume (Vw+cm)	0.261	0.263	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.	8 1/4	6	3 3/4	5 1/4	8	8	4 1/4	3	5	5 1/4	3 1/2	1 3/4
ASTM C138, Density, lb/ft^3	156.1	156.5	155.3	153.7	156.5	158.5	154.1	155.5	155.5	155.3	154.0	152.3
ASTM C138, Gravimetric Air, %	3.8	2.8	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	2.4	2.5	2.4	1.8	1.6	2.4	2.8	1.9	2.1	2.0	4.2
ASTM C1064, Temperature, °F	72	70	72	72	70	70	70	70	70	70	70	70
Resistance Measurement												
Resistance, Ω	39.3	43.7	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	2.0	3.0	0.0	4.0	3.0	2.0	3.0	5.0	0.0	0.0
90min Reading, Ω	38.0		36.0	32.0								
After 90min Simulated Mixing, Ω	44.0		38.0	32.3								
42d Strength (ASTM C39)												
Strength, psi	11250	9870	9300	7470	10200	11460	7010	8370	8320	7540	6470	6660

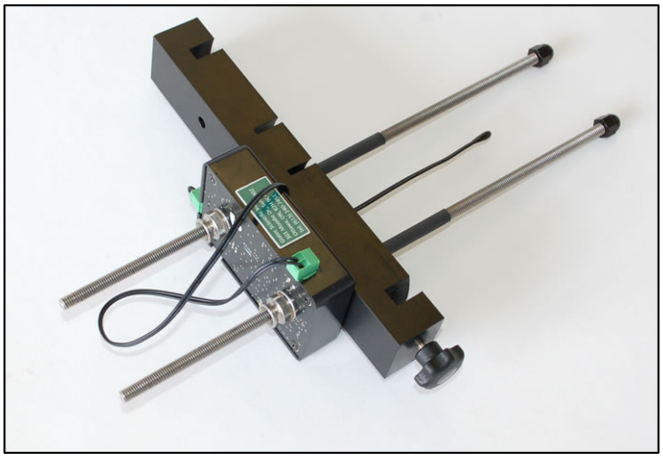

Figure 1 Wireless Device to Measure Resistance of Freshly Mixed Concrete (courtesy of Giatec)

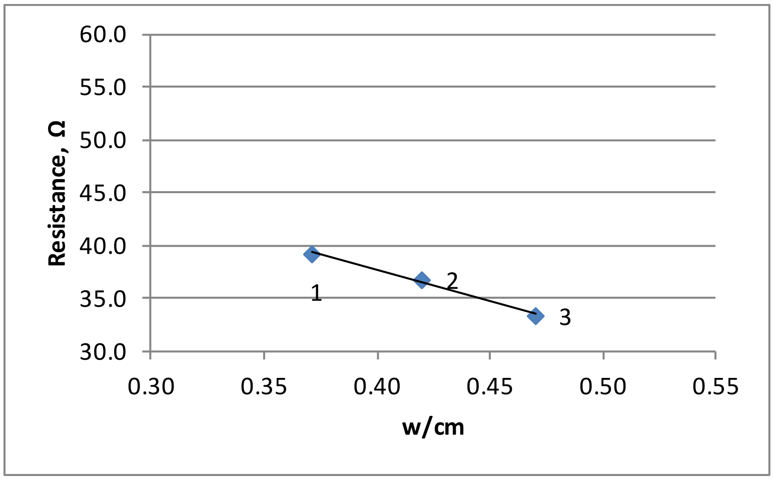

Figure 2 Resistance vs w/cm for Mixtures 1, 2 and 3

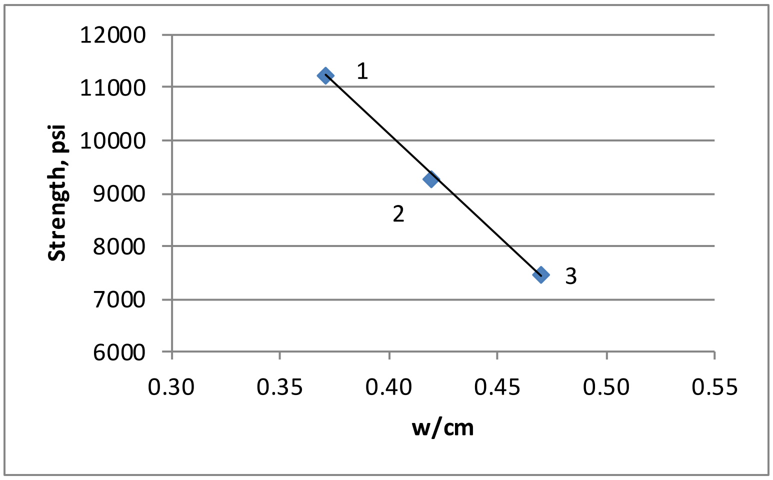

Figure 3 Strength vs w/cm for Mixtures 1, 2 and 3

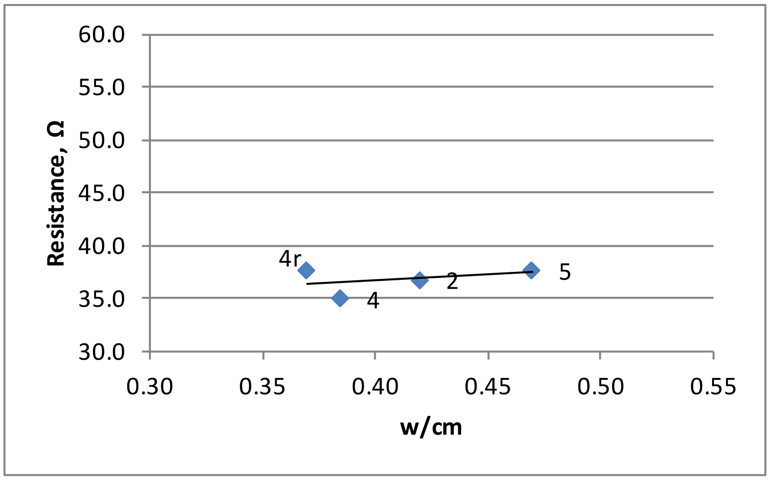

Figure 4 Resistance vs w/cm for Mixtures 2, 4, 4R and 5

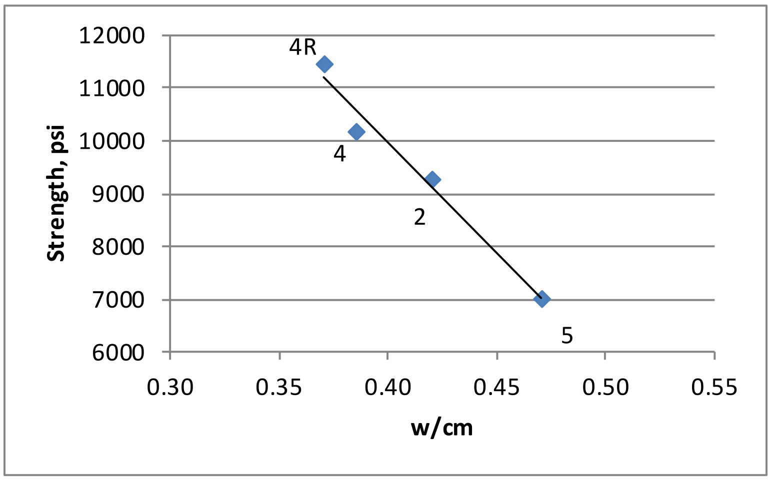

Figure 5 Strength vs w/cm for Mixtures 2, 4, 4R and 5

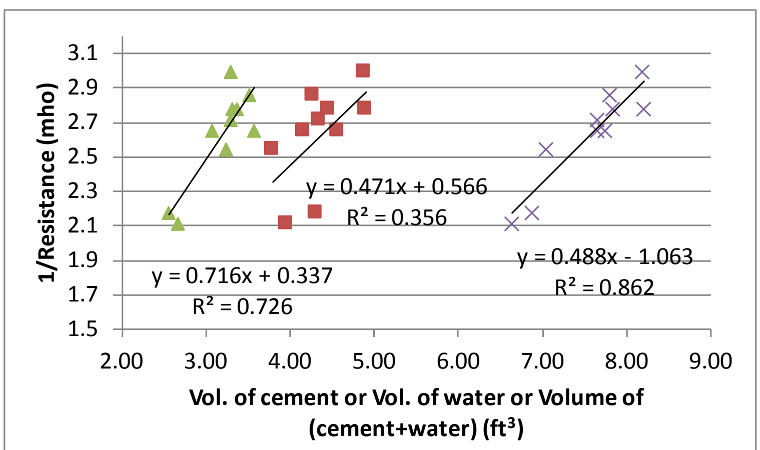

Figure 6 Inverse of Resistance vs volume of cement or volume of water or volume of cement and water for all mixtures prepared with the low alkali cement

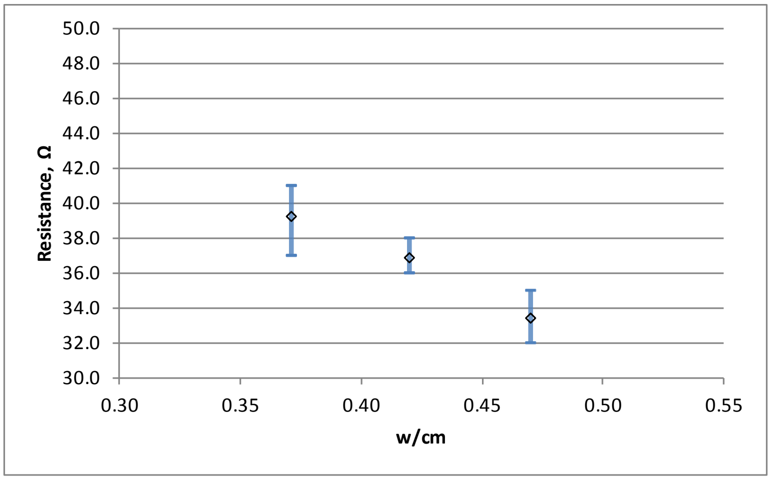

Figure 7 Resistance Range vs w/cm for Mixtures 1, 2 and 3

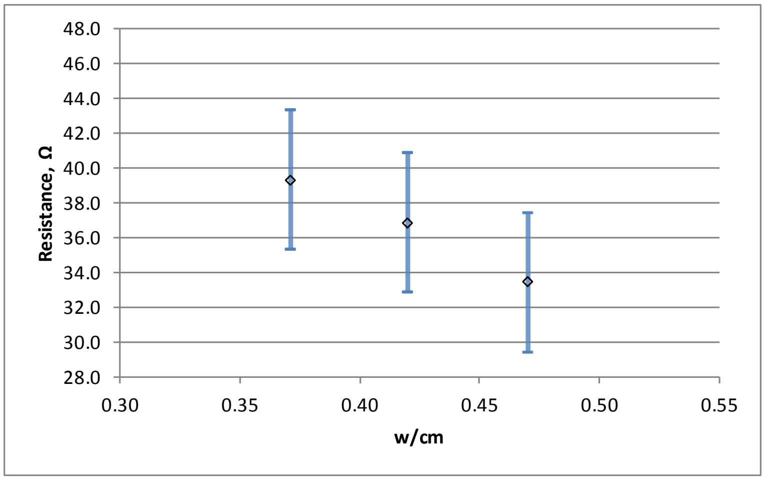

Figure 8 Suggested Specification Limits for Resistance as Indicator for w/cm (using average data from Mix 1, 2, 3)

Appendix – Resistance Measurement and Time for Mixtures 1-10

Mixture ID	Cylinder ID	Resistance Device1			Resistance Device2		
		Time after Mixing, min	Resistance Readings, Ω	Operator	Time after Mixing, min	Resistance Readings, Ω	Operator
1	A	14	40	Operator1	19	41	Operator2
	B	17	40		24	40	
	C	20	37		28	37	
	D	24	38		37	40	
	E	29	40		33	41	
	F	33	38		42	39	
	E	90	38				
	G				86	44	
	H				90	44	
	I				94	44	
2	A	16	36	Operator1	17	36	Operator2
	B	20	37		21	36	
	C	37	36		29	38	
	D	32	37		37	38	
	E	46	37		44	38	
	F	43	36		48	37	
	F				90	36	
	G	94	38				
	H	100	38				
	I	105	38				
3	A	23	33	Operator1	18	34	Operator2
	B	18	33		22	32	
	C	30	33		25	34	
	D	26	34		30	34	
	E	37	33		33	33	
	F	33	35		37	33	
	E	90	32				
	G				100	31	
	H				105	33	
	I				109	33	

Mixture ID	Cylinder ID	Resistance Device1		Resistance Device2	
		Time after Mixing, min	Resistance Readings, Ω	Time after Mixing, min	Resistance Readings, Ω
4	A	17	35		
	B	21	35		
	C	25	35		
4r	A	12	40		
	B	15	36		
	C	20	37		
5	A			15	39
	B			19	38
	C			24	36
6	A			21	48
	B			28	46
	C	31	48		
7	A			18	47
	B			21	47
	C			30	44
8	A			18	27
	B	17	23		
	C	21	22		
9	A			20	36
	B			22	36
	C			28	36
10	A			20	36
	B	18	36		
	C	22	36		