TECHNICAL REPORT STANDARD PAGE

1. Report No. **FHWA/LA.13/496**	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle **Evaluation of Surface Resistivity Measurements as an Alternative to the Rapid Chloride Permeability Test for Quality Assurance and Acceptance – Implementation Report**	**5. Report Date** October 2012 **6. Performing Organization Code** LTRC Project Number: 10-1C State Project Number: 30000152	
7. Author(s) Tyson D. Rupnow, Patrick Icenogle	**8. Performing Organization Report No.**	
9. Performing Organization Name and Address Louisiana Transportation Research Center 4101 Gourrier Avenue Baton Rouge, LA 70808	**10. Work Unit No.** **11. Contract or Grant No.**	
12. Sponsoring Agency Name and Address Louisiana Department of Transportation and Development P.O. Box 94245 Baton Rouge, LA 70804-9245	**13. Type of Report and Period Covered** **Implementation Report** **05/11 – 06/12** **14. Sponsoring Agency Code**	

15. Supplementary Notes
Conducted in Cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract
Many contracting agencies currently use permeability specifications in portland cement concrete (PCC) pavements and structures. This project followed the implementation of the surface resistivity test (TR 233) on a field project in Louisiana. Additionally, a precision statement was developed for TR 233, and a ruggedness study was conducted to determine influencing factors on the results of TR 233 testing.

The single operator coefficient of variation of a single test result has been found to be 2.2 percent. Therefore, the results of two properly conducted tests by the same operator on concrete samples from the same batch and of the same diameter should not differ by more than 6.2 percent. The multilaboratory coefficient of variation of a single test result has been found to be 3.9 percent. Therefore the results of two properly conducted tests in different laboratories on the same material should not differ by more than 11 percent.

The collected data only covered the moderate, low, and very low permeability classes; because of this, the precision statement should only be used for values within these ranges. Further testing is recommended to investigate values in the high and negligible permeability classes. The surface resistivity test shows lower variability than rapid chloride permeability test.

The ruggedness study showed age and aggregate type as significant factors for surface resistivity. An additional factorial was used to compare individual factors against a control sample. The additional factorial suggested age, calcium nitrite, aggregate size, and aggregate type as significant factors for surface resistivity. However, comparative rapid chloride permeability testing on the same sample sets concluded that all significant factors determined will either affect the permeability of the sample in general or influence rapid chloride permeability as well.

The project specific cost benefit analysis showed that the Department saved a total of about $10,000 over three months, $40,000 for a full year, or $160,000 for the life of the construction project, for the Caminada Bay Bridge project after implementing the surface resistivity meter. Using a conservative savings of about $20,000 per year per project and an average of 50 projects per year, the Department is projected to save about $1,000,000 in operational costs when the surface resistivity test is implemented statewide. The savings for contractor QC are expected to equal or exceed DOTD operational cost savings when the surface resistivity test is fully implemented due to the specifications requiring that the contractor conduct QC testing at a frequency equal to or greater than the frequency of QA testing by the Department.

17. Key Words surface resistivity, concrete permeability, chloride ion penetration		**18. Distribution Statement** **Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.**	
19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	21. No. of Pages 48	22. Price

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Evaluation of Surface Resistivity Measurements as an Alternative to the Rapid Chloride Permeability Test for Quality Assurance and Acceptance – Implementation Report

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LTRC Project No. 10-1C
State Project No. 736-99-1661

conducted for

Louisiana Department of Transportation and Development
Louisiana Transportation Research Center

October 2012

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The collected data only covered the moderate, low, and very low permeability classes; because of this, the precision statement should only be used for values within these ranges. Further testing is recommended to investigate values in the high and negligible permeability classes. The surface resistivity test shows lower variability than rapid chloride permeability test.

The ruggedness study showed age and aggregate type as significant factors for surface resistivity. An additional factorial was used to compare individual factors against a control sample. The additional factorial suggested age, calcium nitrite, aggregate size, and aggregate type as significant factors for surface resistivity. However, comparative rapid chloride permeability testing on the same sample sets concluded that all significant factors determined will either affect the permeability of the sample in general or influence rapid chloride permeability as well.

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ACKNOWLEDGMENTS

The U.S. Department of Transportation, Federal Highway Administration (FHWA), Louisiana Department of Transportation and Development (LADOTD), and Louisiana Transportation Research Center (LTRC) financially supported this research project. The efforts of Greg Tullier, Randell Randolph, Don George, Paul Dugas and Katie Johnson in the concrete laboratory are greatly appreciated.

IMPLEMENTATION STATEMENT

LADOTD has implemented the surface resistivity test into DOTD practice and is currently testing the permeability of concrete using DOTD TR 233. The preliminary cost benefit analysis showed that implementation of surface resistivity measurements in lieu of rapid chloride permeability tests will save the Department about $101,000 in personnel costs in the first year of implementation. Additional savings to LADOTD, through savings to suppliers and contractors, was estimated to be about $1.5 million. The project specific cost benefit analysis showed that the Department saved a total of about $10,000 over three months, $40,000 for a full year, or $160,000 for the life of the construction project, for the Caminada Bay Bridge project after implementing the surface resistivity meter. Using a conservative savings of about $20,000 per year per project and an average of 50 projects per year, the Department is projected to save about $1,000,000 in operational costs when the surface resistivity test is implemented statewide. The savings for contractor QC are expected to equal or exceed DOTD operational cost savings when the surface resistivity test is fully implemented due to the specifications requiring that the contractor conduct QC testing at a frequency equal to or greater than the frequency of QA testing by the Department

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INTRODUCTION

Until recently, the rapid chloride permeability test, ASTM C1202, was the only test that quickly determined concrete's ability to resist chloride ion penetration. Recent advances in surface resistivity measurements, and their correlations to the rapid chloride permeability results, have led many owners to use them for a variety of reasons: the first being low cost of the equipment, and the second being a reduction in the number of hours required to conduct the test.

The Louisiana Department of Transportation and Development (LADOTD) recently conducted a study investigating the use of a surface resistivity device as an indication of concrete's ability to resist chloride ion penetration for quality assurance (QA) applications and acceptance of high performance concrete (HPC). The findings of the study showed a very good correlation (R^2 = 0.89) between the surface resistivity device and the rapid chloride permeability test [*1*].

The excellent results led to immediate implementation of surface resistivity testing on the Caminada Bay Bridge project in Louisiana. A test procedure was developed for LADOTD, a surface resistivity meter was purchased for each district, and statewide training was performed for district laboratory personnel. A supplemental specification was created for on-going LADOTD projects that required rapid chloride permeability. Samples were accepted at 28-days of age with passing surface resistivity measurements; however, failed specimens still required rapid chloride permeability testing at 56-days of age.

This report details the documented cost savings of using a surface resistivity meter in place of rapid chloride permeability testing for the Caminada Bay Bridge project. A precision test and ruggedness test performed to obtain a greater understanding of the limitations of the surface resistivity device are also documented in this report.

Literature Review

The authors have completed a detailed literature review noting the correlation of surface resistivity to the rapid chloride permeability test as noted here [*1*].

ASTM C1202 shows the single operator COV of 12.3 percent (1s%) and 42 percent (d2s%) and multilaboratory COV of 18 percent (1s%) and 51 percent (d2s%) [*2*]. Prior to the precision study, the only documented precision for surface resistivity was a draft AASHTO test method, which is now AASHTO TP 95-11. The draft test method only shows a single operator precision of 6.3 percent (1s%) and 21 percent (d2s%) [*3*]. The precision in the draft test method was also developed using an older model of the surface resistivity meter shown to have problems, which were corrected for the newer model [*1*].

Throughout the literature, there are concerns with various factors that could affect the results of the surface resistivity meter. Calcium nitrite, reinforcing steel, and curing method are noted as potentially impacting rapid chloride permeability results using ASTM C-1202 [*2*]. The AASHTO and Florida test procedures note calcium nitrite in the mixture, lime water curing, and temperature during testing [*3, 4*]. Spragg et al. include probe spacing, geometry of the sample, aggregate size, temperature, and surface moisture conditions as factors that can influence measured electrical response [*5*]. Kessler et al. show the effects of curing conditions, the time delay between removing a specimen from the humidity room and testing, and alignment of the meter [*6*]. Morris et al. show effects of aggregate size and type [*7*]. Preliminary results from an ongoing study at the University of North Carolina Charlotte suggest surface resistivity measurements of recycled brick masonry aggregate concrete are greatly impacted across a large temperature range [*8*].

OBJECTIVE

The objective of this research was to implement the surface resistivity meter, determine its precision, and conduct a ruggedness study.

SCOPE

To meet the objectives of this project, field samples from the Caminada Bay Bridge project were tested. Samples were produced under laboratory conditions for the precision study and tested for surface resistivity at ages ranging from 28 days to one year. Samples were produced under laboratory conditions for the ruggedness study and tested for surface resistivity at 14, 28, and 56 days of age. All precision and ruggedness data collection were performed using the newer model of surface resistivity meter.

METHODOLOGY

Test Methods

Precision

The surface resistivity test was conducted according to DOTD TR 233 "Test Method for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration" [*9*]. Table 1 shows the laboratory mixtures used for the precision study. The concrete samples used in the precision study were previously produced throughout the course of other ongoing LTRC concrete research projects. The eight mixtures were tested at various ages, but covered nearly the entire range of permeability classes except the high and negligible permeability classes as defined in TR 233 [*9*]. All concrete samples cast and tested in this study were 4 x 8 in. (100 x 200 mm) cylinders. Note that the surface resistivity test is non-destructive; therefore, all seventeen technicians with his or her own surface resistivity meters tested the same sample sets. To reduce possible error, samples sets were produced, cured, and tested at the LTRC concrete laboratory. The coarse and fine aggregate used in the mixtures were #67 limestone and natural river sand, respectively. Super plasticizer was used to maintain workability.

Table 1
Laboratory mixtures used for the precision study

Mixture	Portland Cement (lb/yd^3)	Grade 120 Slag (lb/yd^3)	Class C Fly Ash (lb/yd^3)	Class F Fly Ash (lb/yd^3)	Water (lb/yd^3)	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)
A	564				282	1830	1190
B	200	150		150	225	1951	1222
C	150	150	200		225	1951	1234
D	100	250		150	225	1951	1217
E	200		150	150	225	1951	1209
F	100		200	200	225	1951	1188
G	50	250		200	225	1951	1204
H	300		100	100	225	1951	1227

Ruggedness

Table 2 shows the factors included in the ruggedness study. Daracem 55 was used as a water reducer and also as the calcium nitrite source; all other mixtures used Zyla 620 as a water reducer. Segregation in cylinders was artificially created by vibrating the cylinders while slowly pressing the larger aggregate down. Daravair 1000 was used as the air entrainment admixture. The temperatures selected for the ruggedness factor represent the average temperature and the maximum allowed temperature in surface resistivity test methods. A temperature control cylinder with embedded thermal couple was made from the control mixture. The temperature control cylinder was placed in the water with specimens requiring temperature conditioning in order to determine when the center of the cylinders was at the designated temperature. Due to the non-destructive nature of surface resistivity, specimens tested at 14-days of age were also tested at 56-days of age to simulate two ruggedness comparisons. Specimens requiring the meter to be offset from center were always tested with the meter offset 1.25 inches toward the top of the cylinder.

Table 2
Factors included in the ruggedness study

Factor	Variable	Discussion	Level 1 (-)	Level 2 (+)
A	Aggregate Type	Type of coarse aggregate	Gravel	Limestone
B	Aggregate Size	Size of coarse aggregate	#57	#67
C	Calcium Nitrite	Presence of Calcium Nitrite in mixture	Yes	No
D	Lime Water Curing	Curing in lime water tank	Yes	No
E	Segregated Cylinder	Segregation of aggregate in cylinder by vibration	Yes	No
F	Air Admixture	Presence of air admixture (0.50 oz/cwt)	Yes	No
G	Temperature	Conditioning temperature (water controlled)	76F	73F
H	Surface Moisture	Time of drying after saturated surface dry (temperature is air controlled for the 15 min)	SSD + 15 minutes	SSD + 0 minutes
I	Age	Age at measurement	14/56 day	28 day
J	Meter Offset	Off set pegs from center of longitudinal side, placement at 1.25 inch from center	1.25"	0"
K	Collection Pattern	Collecting 8 measurements in one revolution instead of standard 4 in two revolutions	8x1	4x2

A partial factorial with foldover was setup using Plackett-Burman design described in ASTM E1169 [*10*]. An extra factorial was included with the ruggedness study to compare the effects of each factor against a control sample at 14, 28, and 56-days of age. A few of the factors are not mixture specific; therefore, the ruggedness factorial could be represented by sixteen mixtures. Table 3 shows the mix proportions for the ruggedness study. Rapid chloride permeability testing was also performed on specimens from the extra factorial at 14 and 28-days of age to determine if factors of the ruggedness study were affecting the results of the surface resistivity meter or permeability of the specimen in general.

Analysis Techniques

ASTM C802 and ASTM C670 were used to analyze the data for the precision study [*11*, *12*]. A total of seventeen laboratories and eight mixtures were tested. The average result of three specimens was considered a sample.

ASTM E1169 was used to analyze the data for the ruggedness study [*10*]. Student t-tests were performed on the additional factorial to compare the effects of changing one of the factor levels against a control. The ruggedness factorial included 24 combinations of factors and the extra factorial included 11 additional combinations for a total of 35 unique combinations of factors, shown in Table 4. The average result of three specimens was considered a sample.

Table 3
Mixture proportions for ruggedness study

Mixture	Portland Cement (lb/yd^3)	Class C Fly Ash (lb/yd^3)	Water (lb/yd^3)	Coarse Aggregate Limestone (lb/yd^3)	Coarse Aggregate Gravel (lb/yd^3)	Fine Aggregate (lb/yd^3)	Air Entrain Daravair (oz/cwt)	Water Reducer Zyla 620 (oz/cwt)	Water Reducer Daracem 55 (oz/cwt)
1	451	113	282	1946		1276		5.0	
2*	451	113	282	1946		1276		5.0	
3	451	113	282	1946		1276			6.0
4*	451	113	282	1946		1276			6.0
5	451	113	282	1784		1170	0.5	5.0	
6*	451	113	282	1784		1170	0.5	5.0	
7	451	113	282	1784		1170	0.5		6.0
8*	451	113	282	1784		1170	0.5		6.0
9	451	113	282		1872	1240		5.0	
10*	451	113	282		1872	1240		5.0	
11	451	113	282		1872	1240			6.0
12*	451	113	282		1872	1240			6.0
13	451	113	282		1715	1138	0.5	5.0	
14*	451	113	282		1715	1138	0.5	5.0	
15	451	113	282		1715	1138	0.5		6.0
16*	451	113	282		1715	1138	0.5		6.0

* represents #57 size aggregate

Table 4
Ruggedness factorial combinations

ID	Mixture	A	B	C	D	E	F	G	H	I	J	K
R1	**3**	1	1	-1	1	1	1	-1	-1	-1	1	-1
R2	**9**	-1	1	1	-1	1	1	1	-1	-1	-1	1
R3	**2**	1	-1	1	1	-1	1	1	1	-1	-1	-1
R4	**15**	-1	1	-1	1	1	-1	1	1	1	-1	-1
R5	**10**	-1	-1	1	-1	1	1	-1	1	1	1	-1
R6	**12**	-1	-1	-1	1	-1	1	1	-1	1	1	1
R7	**8**	1	-1	-1	-1	1	-1	1	1	-1	1	1
R8	**3**	1	1	-1	-1	-1	1	-1	1	1	-1	1
R9	**5**	1	1	1	-1	-1	-1	1	-1	1	1	-1
R10	**13**	-1	1	1	1	-1	-1	-1	1	-1	1	1
R11	**6**	1	-1	1	1	1	-1	-1	-1	1	-1	1
R12	**16**	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
F1	**14**	-1	-1	1	-1	-1	-1	1	1	1	-1	1
F2	**8**	1	-1	-1	1	-1	-1	-1	1	1	1	-1
F3	**15**	-1	1	-1	-1	1	-1	-1	-1	1	1	1
F4	**2**	1	-1	1	-1	-1	1	-1	-1	-1	1	1
F5	**7**	1	1	-1	1	-1	-1	1	-1	-1	-1	1
F6	**5**	1	1	1	-1	1	-1	-1	1	-1	-1	-1
F7	**9**	-1	1	1	1	-1	1	-1	-1	1	-1	-1
F8	**14**	-1	-1	1	1	1	-1	1	-1	-1	1	-1
F9	**12**	-1	-1	-1	1	1	1	-1	1	-1	-1	1
F10	**4**	1	-1	-1	-1	1	1	1	-1	1	-1	-1
F11	**11**	-1	1	-1	-1	-1	1	1	1	-1	1	-1
F12	**1**	1	1	1	1	1	1	1	1	1	1	1
X1	**1**	1	1	1	1	1	1	1	1	1	1	1
X2	**9**	-1	1	1	1	1	1	1	1	1	1	1
X3	**2**	1	-1	1	1	1	1	1	1	1	1	1
X4	**3**	1	1	-1	1	1	1	1	1	1	1	1
X5	**1**	1	1	1	-1	1	1	1	1	1	1	1
X6	**1**	1	1	1	1	-1	1	1	1	1	1	1
X7	**5**	1	1	1	1	1	-1	1	1	1	1	1
X8	**1**	1	1	1	1	1	1	-1	1	1	1	1
X9	**1**	1	1	1	1	1	1	1	-1	1	1	1
X10	**1**	1	1	1	1	1	1	1	1	1	-1	1
X11	**1**	1	1	1	1	1	1	1	1	1	1	-1

R = Ruggedness Factorial, F = Foldover, X = Extra Factorial, -1 = Level 1 Factor, 1 = Level 2 Factor

DISCUSSION OF RESULTS

Precision Study Results

Table 5 shows the fresh concrete properties for the concrete mixtures used in the precision study.

Table 5
Fresh concrete properties for the concrete mixtures used in the precision study

Mixture	Air Content (%)	Slump (in)
A	1.3	4.50
B	2.9	1.50
C	3.4	1.00
D	4.4	0.50
E	5.4	6.00
F	4.2	8.50
G	3.4	7.50
H	5.1	5.50

During data collection, multiple operators questioned the measured values from one specimen of one sample set. Initial analysis of the data showed all operators recorded the specimen in question consistently measuring about 100 kΩ-cm lower than the other five specimens from the mixture. Further inspection showed a distinct difference in color and visible void structure on the surface of the specimen. The specimen was mistakenly taken from another mixture with a similar laboratory identification number. The specimen was removed from the sample set and the remaining two specimens were used for the average.

The within-laboratory variances in different laboratories are assumed the same for analysis with ASTM C802 [*11*]. An investigation of agreement of variances showed one variance on the borderline of exceeding the ratio of largest variance to sum of variances. For analysis in this study, all variances were considered in agreement. Table 6 shows the laboratory averages and variances. A check for interactions between laboratories and materials was performed by plotting the averages of each material to verify similar patterns of change from material to material across all laboratories. Figure 1 shows similar patterns for all laboratories, which indicates no interactions.

Table 6
Lab averages kΩ-cm (lab variances)

	Material							
Lab	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
1	14.6 (0.003)	128.3 (0.038)	153.7 (84.771)	169.1 (2.136)	25.5 (0.633)	27.6 (0.02)	239.9 (1.32)	58.2 (0.605)
2	14.7 (0.002)	125.2 (0.883)	148.4 (7.283)	165.3 (0.056)	24.9 (0.771)	26.9 (0.009)	226.4 (7.801)	55.3 (3.094)
3	15.3 (0.175)	131.2 (0.573)	163.8 (0.342)	180.9 (9.607)	24.8 (0.046)	28.7 (0.409)	230 (9.957)	57.2 (1.877)
4	15.1 (0.013)	132.7 (0.642)	165.1 (20.922)	182.7 (4.5)	27.5 (0.776)	30.5 (0.001)	228.1 (3.804)	60.7 (0.015)
5	15 (0.009)	130 (1.673)	165.1 (3.396)	177.2 (85.363)	26.2 (1.568)	29.2 (0.121)	235.1 (42.014)	57.3 (0.766)
6	15.2 (0.001)	139.9 (0.405)	171.7 (53.066)	195.6 (7.524)	26.6 (1.382)	28.7 (0.013)	231.9 (25.353)	59.2 (2.95)
7	14.9 (0.129)	130.4 (1.983)	165.1 (3.188)	181.5 (28.25)	25.8 (1.583)	28.5 (0.024)	220.8 (12.231)	56.6 (2.92)
8	15 (0.075)	128.9 (0.017)	153.8 (0.492)	166.8 (72.651)	25.4 (1.445)	27.8 (0.111)	212.2 (0.073)	55.8 (2.991)
9	14.9 (0.014)	120.3 (0.94)	149.3 (7.67)	167.3 (3.489)	25 (0.656)	27.9 (0)	220.5 (194.702)	56.4 (0.401)
10	15 (0.026)	121.8 (0.447)	151.1 (0.062)	161.7 (0.878)	25.4 (1.354)	27.5 (0.033)	210.2 (28.156)	54.7 (2.278)
11	15.2 (0.041)	122.3 (3.032)	151.2 (9.272)	164.3 (2.383)	25.5 (1.424)	27.6 (0.098)	215.1 (11.903)	56.2 (2.81)
12	15.2 (0.01)	126.1 (1.334)	154 (0.14)	164.4 (39.346)	25.8 (1.524)	28 (0.024)	219.5 (52.318)	55.6 (0.771)
13	15.3 (0.17)	127.6 (2.059)	153.9 (1.351)	165.7 (18.605)	25.6 (1.368)	28.2 (0)	205.6 (0.111)	54.7 (2.761)
14	15.8 (0.06)	127.8 (0.006)	157.1 (2.747)	173.1 (13.09)	26.5 (1.605)	28.9 (0.31)	222.3 (32.368)	57.7 (1.829)
15	15 (0.144)	123.5 (0.569)	149.2 (40.014)	167.6 (6.272)	26.3 (0.628)	28.6 (0.368)	217.5 (0.07)	56.1 (2.042)
16	15 (0.045)	124.3 (0.023)	151.3 (23.163)	165.6 (16.868)	25.7 (1.027)	28 (0.046)	211.7 (0.131)	55.3 (1.459)
17	15.2 (0.051)	131.8 (0.479)	159 (0.038)	183.2 (49.17)	26.3 (0.459)	28.2 (0.401)	225.3 (0.856)	56.6 (0.957)

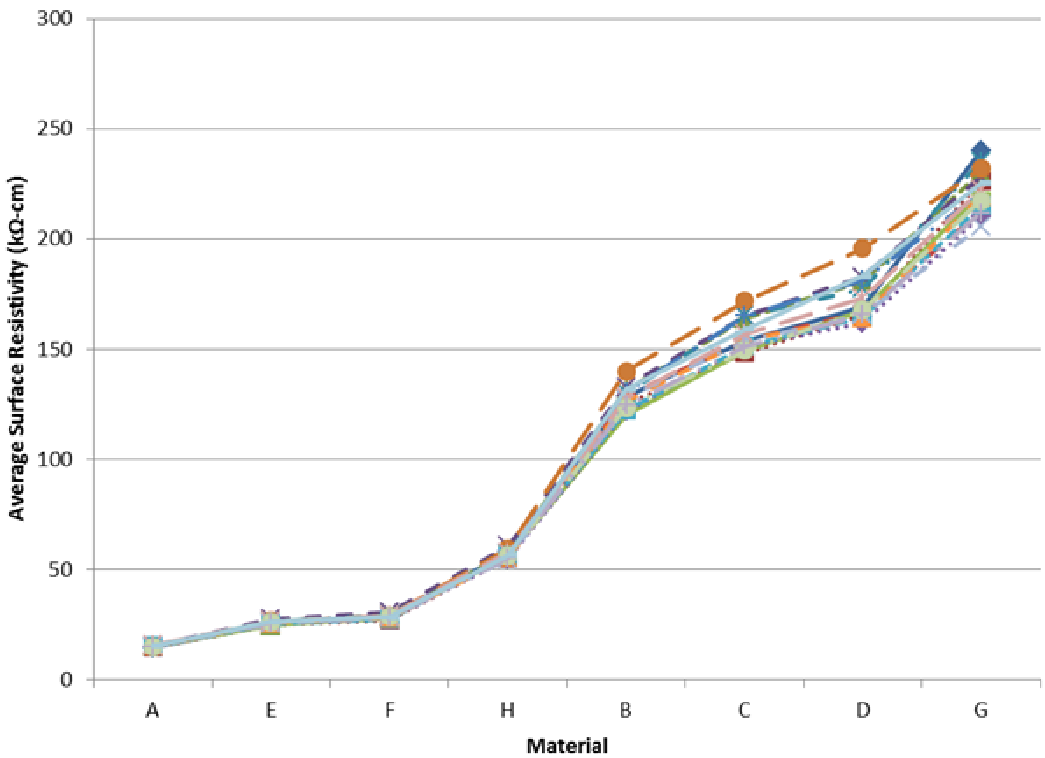

Figure 1
Average surface resistivity by laboratory, sorted by material on increasing surface resistivity

The eight materials used for surface resistivity testing had sample averages ranging from 14.6 to 239.9 kΩ-cm. These values represent the range of moderate, low, and very low permeability classes. Although the presented data covers the majority of the permeability class range, additional testing should be performed to develop a precision statement for high and negligible permeability classes.

Plots of within-laboratory and between-laboratory standard deviations against the material averages show an approximate linear trend, as shown in Figure 2. Plots of coefficient of variations (COV) against the material averages remain relatively constant as shown in Figure 3. The results agree with ASTM C-802, which states the single operator one-sigma limit in percent (1s%) is the average within-laboratory COV and the multilaboratory one-sigma limit in percent (1s%) is the average between-laboratory COV. The average within-laboratory, single operator, COV is 2.2 percent and the average between laboratory, multilaboratory, COV is 3.9 percent.

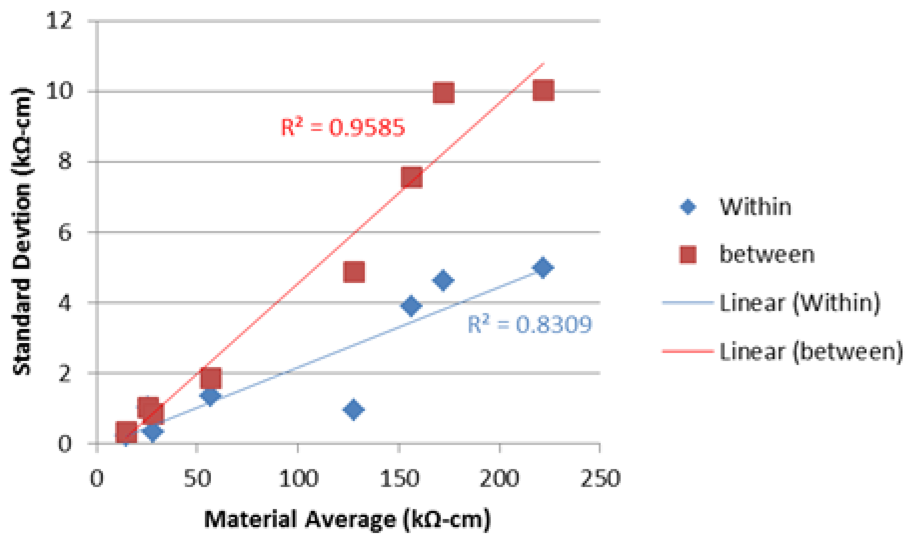

Figure 2
Standard deviation versus the material average

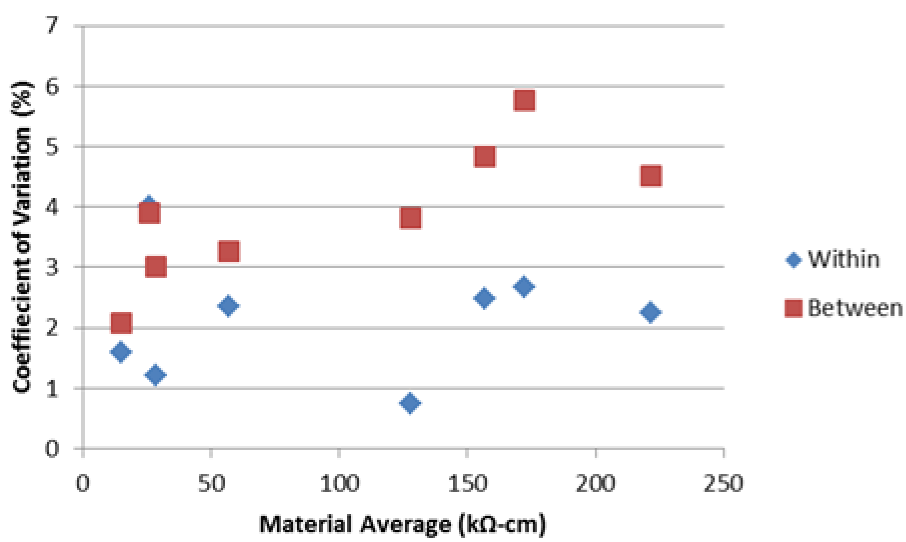

Figure 3
Coefficient of variation versus the material average

Using ASTM C670 the following precision statements were developed for surface resistivity. The single operator coefficient of variation of a single test result was determined to be 2.2 percent (1s%). Therefore, the results of two properly conducted tests by the same operator on concrete samples from the same batch and of the same diameter should not differ by more than 6.2 percent (d2s%). The multilaboratory coefficient of variation of a single test result was determined to be 3.9 percent (1s%). Therefore, the results of two properly conducted tests in different laboratories on the same material should not differ by more than 11 percent (d2s%).

Since the specimens were randomly selected to form two sample sets per mixture, a Monte Carlo simulation was run with 100 iterations to randomly regroup specimens for each mixture. The procedure of ASTM C802 was performed for each iteration and the average within-laboratory and between-laboratory COV was recorded. The simulation yielded an overall average single operator COV of 2.1 percent and an overall average multilaboratory COV of 3.9 percent across the 100 iterations.

Multiple studies have shown a strong relationship exists between the rapid chloride permeability test and the surface resistivity test [*1,2,4,5,6,7*]. ASTM C1202 shows the single operator COV of 12.3 percent (1s%) and 42 percent (d2s%) and multilaboratory COV of 18 percent (1s%) and 51 percent (d2s%) (1). However, the single operator difference between two individual test results in percent (d2s%) does not match the procedure in ASTM C670 *[2]*. AASHTO T-277 shows similar COV, with the exception of the single operator d2s% of 35 percent, which matches the procedure in ASTM C670. The AASHTO draft standard for surface resistivity shows only a single operator precision of 6.3 percent (1s%) and 21 percent (d2s%) *[3]*. The AASHTO standard was created prior to the development of the new meter. The older model meter was known to exhibit error caused by various components that have since been corrected in the new meter design [*1*]. In all cases, the surface resistivity test shows more precision than the rapid chloride permeability test, which confirms the observations of Rupnow et al. [*1*].

Ruggedness Study Results

Table 7 shows the fresh concrete properties for the concrete mixtures used in the ruggedness study.

Table 8 shows the average test result for each combination of the ruggedness and foldover factorial. Note that the combinations including 14-day results were also run at 56 days of age to simulate two ruggedness tests. One test will represent the two levels of the age factor as 14-day (-) and 28-day (+), while the other test will represent the two levels of the age factor as 28-day (+) and 56-day (-). The analysis procedure from ASTM E1169 computes the main effect values for each factor as well as estimated effects of interactions [*10*]. The main effects are ordered by absolute value and plotted as a half-normal plot; see Figure 4 and Figure 5.

Table 7
Fresh concrete properties for the concrete mixtures used in the ruggedness study

Mixture	Air Content (%)	Slump (in)
1	1.5	7.50
2	1.5	8.25
3	2.7	8.50
4	3.0	6.75
5	3.5	10.00
6	2.8	8.75
7	2.6	8.50
8	3.2	9.00
9	2.7	7.25
10	4.5	8.75
11	2.8	7.25
12	2.2	8.50
13	3.9	9.75
14	1.1	8.50
15	2.6	10.50
16	1.6	8.75

Table 8
Ruggedness factorial and foldover average test results

ID	14/28 (kΩ-cm)	28/56 kΩ-cm	ID	14/28 kΩ-cm	28/56 kΩ-cm
R1	8.0	13.4	F1	7.9	7.9
R2	5.8	9.6	F2	9.4	9.4
R3	9.5	14.6	F3	5.7	5.7
R4	6.7	6.7	F4	8.9	13.6
R5	6.5	6.5	F5	9.0	14.2
R6	8.1	8.1	F6	6.1	9.3
R7	7.9	11.4	F7	7.4	7.4
R8	9.0	10.1	F8	6.0	10.5
R9	8.4	8.9	F9	5.4	10.1
R10	6.4	11.6	F10	12.2	12.2
R11	11.3	11.3	F11	6.0	10.3
R12	5.9	9.7	F12	8.7	8.7

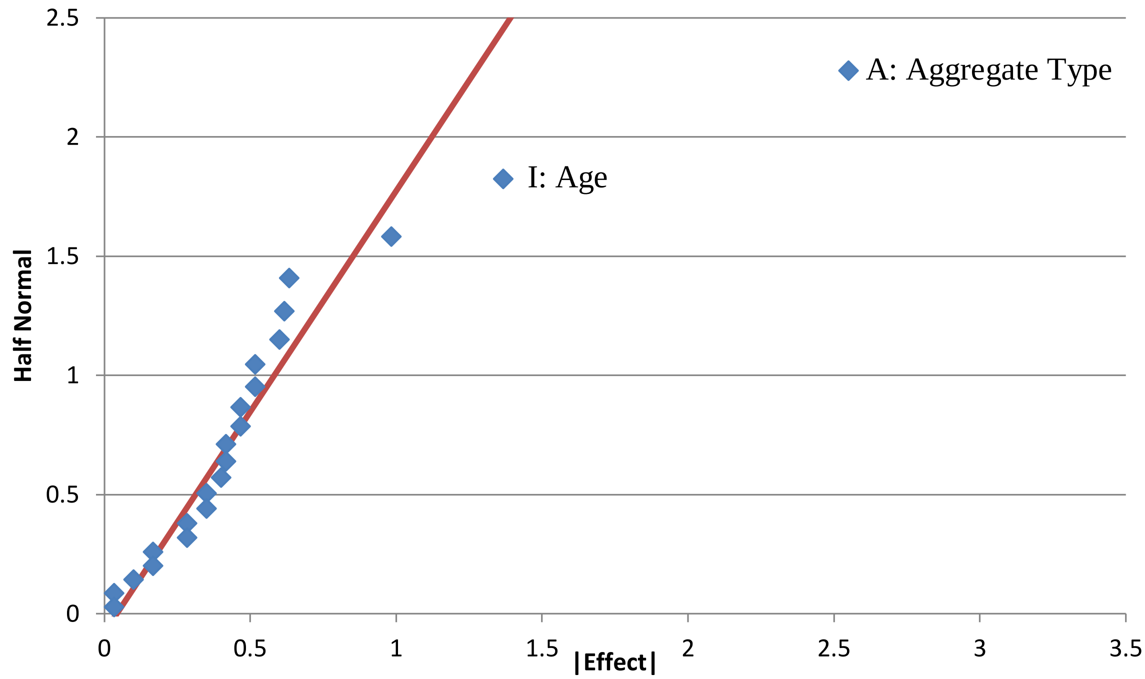

Figure 4
Half –normal plot using 14/28-day data

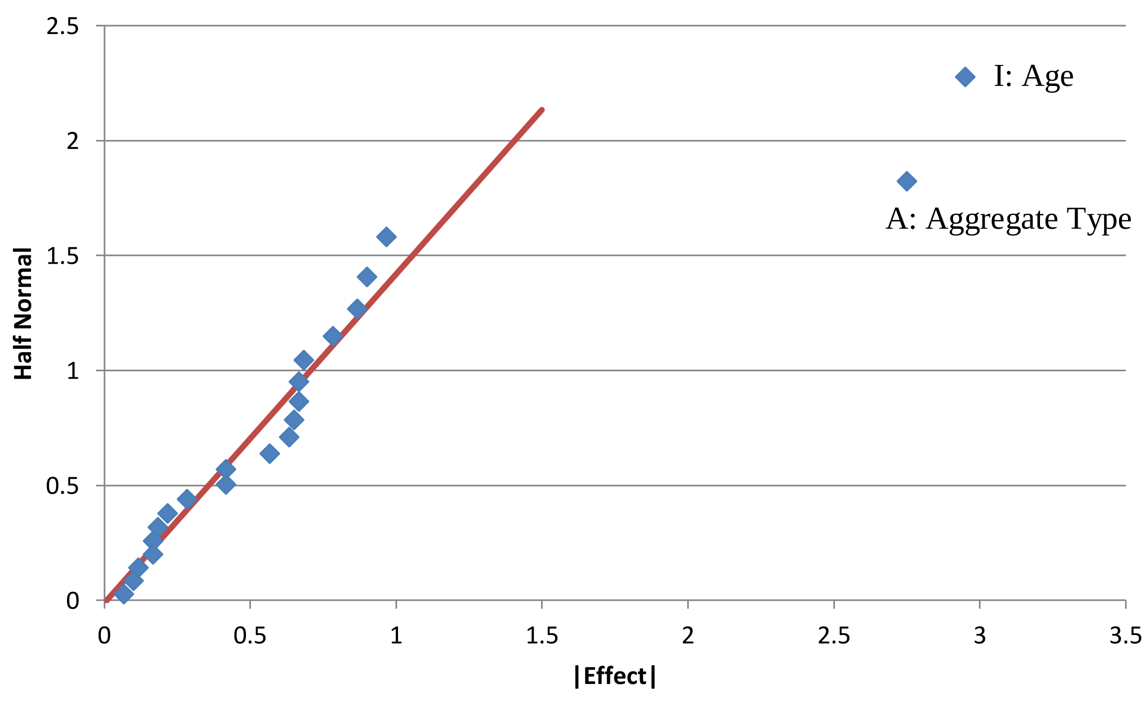

Figure 5
Half-normal plot using 28/56-day data

A line is drawn through the smaller effect estimates, which appear to lie approximately in a straight line. The line represents the standard error for the main effects and interaction estimates. Values falling furthest to the right of the line are potentially significant effects. As shown in Figures 4 and 5, both ruggedness tests show aggregate type and age as potentially significant factors.

The additional factorial represents a control sample using all factors at level 2 (+) and samples only varying one factor at a time to level 1 (-). The additional factorial also allows cylinders from the same sample sets to be tested for rapid chloride permeability in addition to surface resistivity. Table 9 shows the average test results for each sample set of the additional factorial. All values seem reasonable, except for the 14-day rapid chloride permeability result of the sample containing calcium nitrite, which is lower than the 28-day result. ASTM C-1202 does note that tests containing calcium nitrite admixed into concrete can produce misleading results; however, the note states that results are generally higher than similar mixtures without calcium nitrite. This value is believed to be in error.

Table 9
Additional factorial averages

		Surface Resistivity			Rapid Chloride Permeability	
ID	Factor	14-Day (kΩ-cm)	28-Day (kΩ-cm)	56-Day (kΩ-cm)	14-Day (Coulomb)	28-Day (Coulomb)
X1	Control	6.6	8.7	11.6	5603	4316
X2	Aggregate Type	5.6	7.4	10.3	6591	5056
X3	Aggregate Size	9.5	11.2	13.7	4305	3663
X4	Calcium Nitrite	8.2	10.1	13.2	3261	4397
X5	Lime Cure	6.3	8.2	10.9	6757	5330
X6	Segregation	7.0	9.0	11.4	5965	5451
X7	Air Admixture	7.3	8.9	12.0	4853	4468
X8	Temperature	6.3	8.4	10.6		
X9	Surface Moisture	6.8	8.6	12.2		
X10	Meter Offset	6.7	8.6	11.5		
X11	Collection Pattern	6.7	8.7	11.8		

Figure 6 shows a comparison of factors and various ages of surface resistivity testing. Figure 7 shows a comparison of factors of rapid chloride permeability testing. As observed in the precision study, the surface resistivity values of the ruggedness study also exhibited a much lower coefficient of variation than values of the rapid chloride permeability.

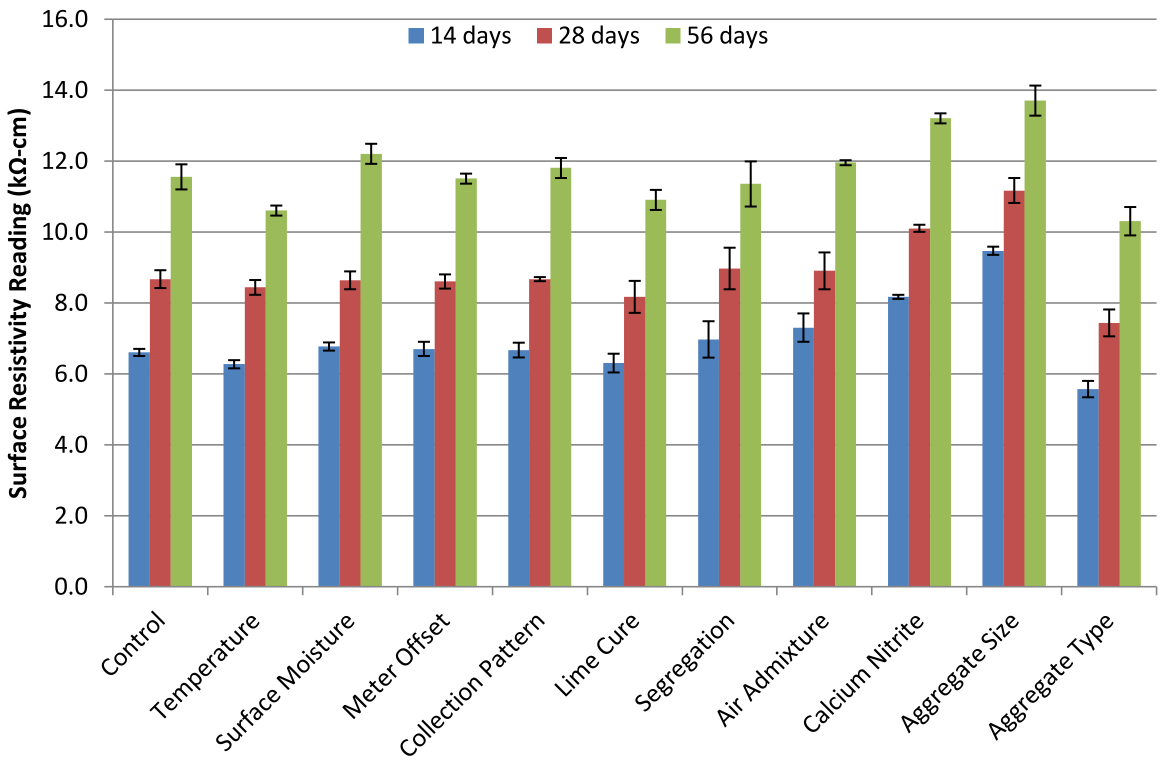

Figure 6
Additional factorial surface resistivity test results

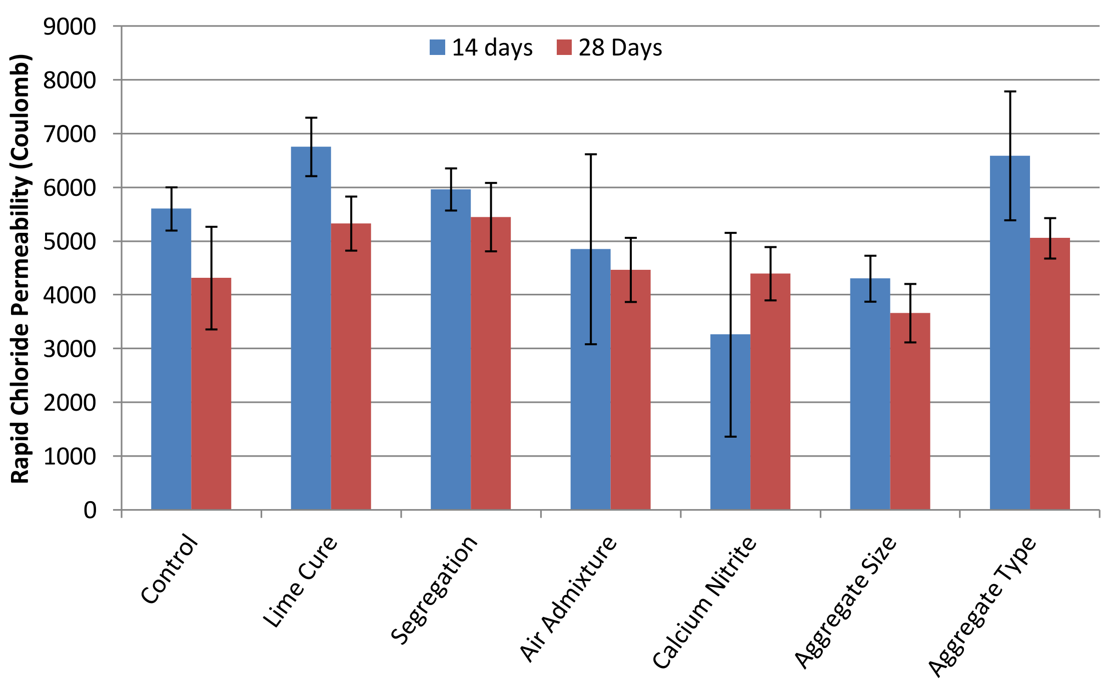

Figure 7
Additional factorial rapid chloride permeability test results

Student t-tests ($\alpha = 0.05$) were performed at each age between the control sample and each factor. The results for surface resistivity show calcium nitrite, aggregate size, and aggregate type factors were significantly different at every age tested. The temperature and air admixture samples were slightly significantly different at some ages. Comparing means, the calcium nitrite sample was 14 to 24 percent higher than the control, which does not follow the note from ASTM C-1202 stating calcium nitrite generally reduces resistance. The aggregate size sample was 19 to 43 percent higher than the control and the aggregate type sample was 11 to 16 percent lower than the control. The percent difference from the control for all significantly different factors reduced with age.

In order to determine if the significant factors influence the surface resistivity meter or concrete permeability in general, the surface resistivity results were plotted against rapid chloride permeability results from the same sample set at the same age. Figure 8 shows that the majority of the data points seem to follow the relationship established from the LTRC report and fall within the curve fit from the LTRC report and curve fit from the AASHTO test procedure. The only data point under the LTRC curve fit is the point corresponding to the unreasonable 14-day calcium nitrite value mentioned previously. These results lead the authors to believe that all significant factors that influence the surface resistivity test either influence the permeability of the sample in general or affect rapid chloride permeability as well.

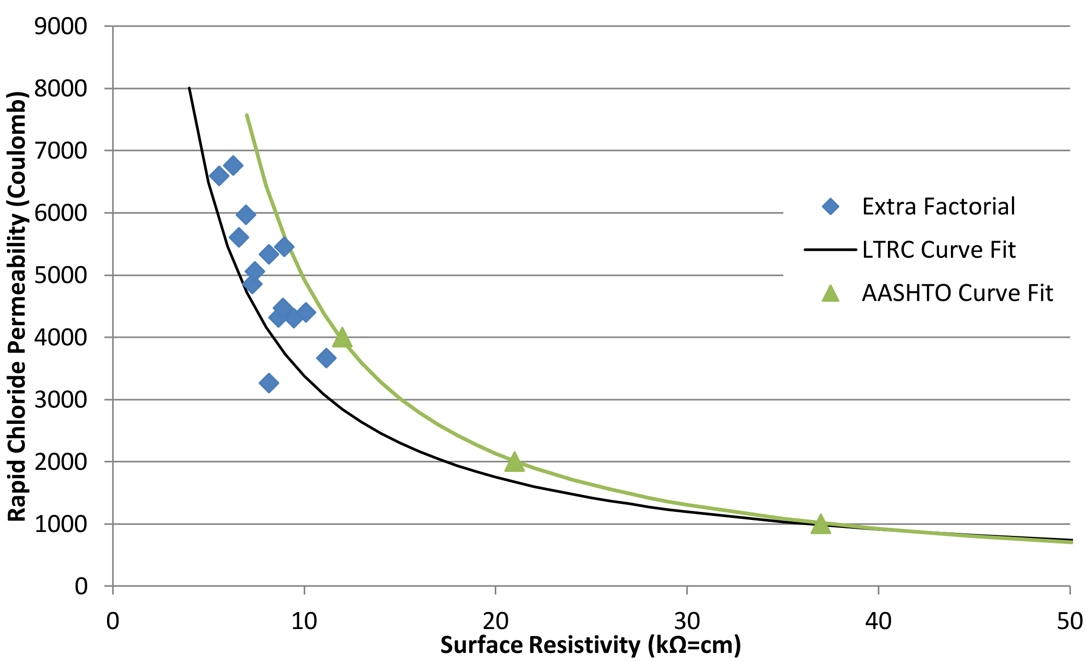

Figure 8
Surface resistivity versus rapid chloride permeability

Implementation Results

The preliminary cost benefit analysis results showed by the authors that implementation of surface resistivity measurements in lieu of rapid chloride permeability tests will save the Department about $101,000 in personnel costs in the first year of implementation [*1*]. The contractors QC savings were estimated to be near $1.5 million [*1*].

A project specific cost benefit analysis was conducted for the Caminada Bay Bridge Project, located on LA 1, in south Louisiana and shown in Figure 9. The implementation project cost benefit analysis accounts for other factors such as mileage and travel time when compared to the preliminary cost benefit analysis.

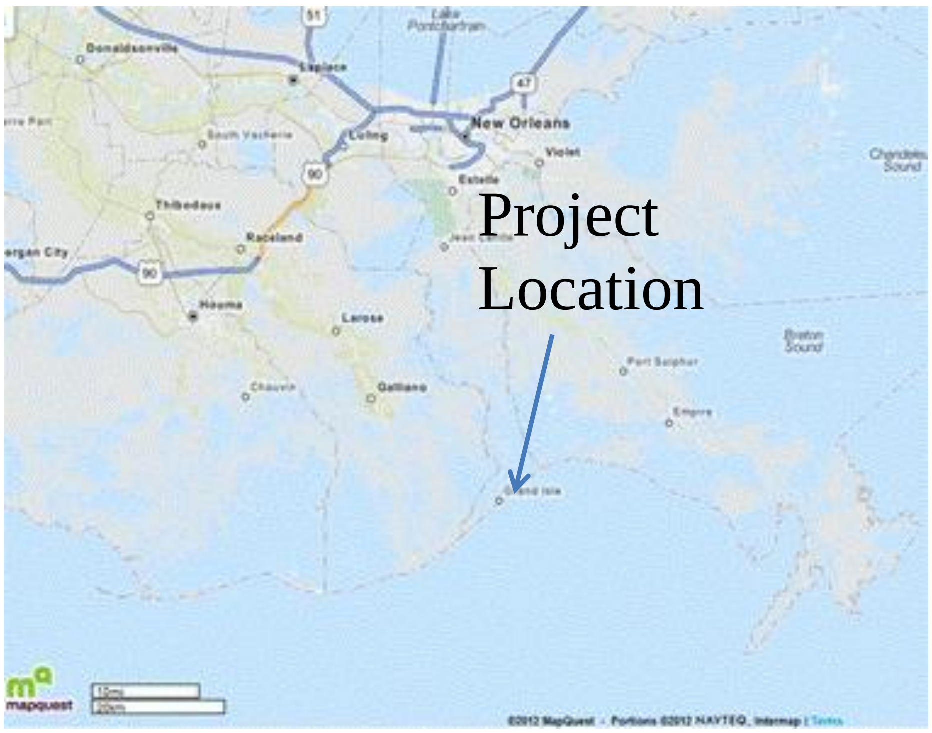

Figure 9
Project location for the Caminada Bay Bridge project

The project was about a 7 hour round trip drive from the LTRC concrete laboratory. Samples were driven from the project location to LTRC for testing (either rapid chloride permeability or surface resistivity). After implementation into the District Laboratory, the travel time was reduced about by 66 percent thus increasing the cost savings. Taking into account one trip per week for three months, or about 12 trips, the technician time savings is about $117 per week or a total savings in travel time of about $1,400. The mileage savings is about $70 per week, assuming 140 miles saved per week times $0.50 per mile. The total mileage savings comes to about $840.

The number of lots tested for the project over the same three months was 43. Using the information set forth by Rupnow and Icenogle for each test method, the cost for the ASTM C1202 testing would have been about $8,042, compared to a cost of about $332 for the surface resistivity testing, or a savings of about $7,711 when comparing the two test methods [*1*]. By implementing the surface resistivity test, the Department saved a total of about $9,951 in three months. The yearly projected savings for the Caminada Bay Bridge project are about $40,000. The surface resistivity test, if implemented at the beginning of the four year construction project, would have save about $160,000 in DOTD operational costs.

The LADOTD Bridge Design Section noted that bridge construction projects typically total between 45 and 60 projects per year for the Department. Note that the majority of these construction projects are much smaller than the aforementioned implementation project. Using a conservative savings of about $20,000 per year per project and an average of 50 projects per year, the Department is projected to save about $1,000,000 in operational costs when the surface resistivity test is implemented statewide.

Note that the savings for contractor QC are expected to equal or exceed DOTD operational cost savings when the surface resistivity test is fully implemented due to the specifications requiring that the contractor conduct QC testing at a frequency equal to or greater than the frequency of QA testing by the Department.

CONCLUSIONS

The results of this study warrant the following conclusions. The single operator coefficient of variation of a single test result has been found to be 2.2 percent. Therefore, the results of two properly conducted tests by the same operator on concrete samples from the same batch and of the same diameter should not differ by more than 6.2 percent.

The multilaboratory coefficient of variation of a single test result has been found to be 3.9 percent. Therefore, the results of two properly conducted tests in different laboratories on the same material should not differ by more than 11 percent.

The collected data only covered the moderate, low, and very low permeability classes; because of this, the precision statement should only be used for values within these ranges. Further testing is recommended to investigate values in the high and negligible permeability classes. The surface resistivity test shows lower variability than rapid chloride permeability test.

The ruggedness study showed age and aggregate type as significant factors for surface resistivity. An additional factorial was used to compare individual factors against a control sample. The additional factorial suggested age, calcium nitrite, aggregate size, and aggregate type as significant factors for surface resistivity. However, comparative rapid chloride permeability testing on the same sample sets concluded that all significant factors determined will either affect the permeability of the sample in general or influence rapid chloride permeability as well.

The project specific cost benefit analysis showed that the Department saved a total of about \$10,000 over three months, \$40,000 for a full year, or \$160,000 for the life of the construction project, for the Caminada Bay Bridge project after implementing the surface resistivity meter. Using a conservative savings of about \$20,000 per year per project and an average of 50 projects per year, the Department is projected to save about \$1,000,000 in operational costs when the surface resistivity test is implemented statewide. The savings for contractor QC are expected to equal or exceed DOTD operational cost savings when the surface resistivity test is fully implemented due to the specifications requiring that the contractor conduct QC testing at a frequency equal to or greater than the frequency of QA testing by the Department.

RECOMMENDATIONS

The authors recommend that a precision study be undertaken to further develop the precision statement for the negligible and high permeability classes as noted in DOTD TR233. A study looking at the amount of cover concrete required for in-situ measurement on reinforced concrete structures needs to be completed. The authors recommend statewide implementation of the surface resistivity meter testing to be conducted in accordance with DOTD TR 233.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
PCC	portland cement concrete
FHWA	Federal Highway Administration
QA	quality assurance
QC	quality control
HPC	high performance concrete
in.	inch(es)
pcf	pounds per cubic foot
LADOTD	Louisiana Department of Transportation and Development
LTRC	Louisiana Transportation Research Center
ASTM	American Society of Testing and Materials
TIG	Technical Implementation Group
w/cm	water to cementitious materials
XRF	X-ray fluorescence
TR	Test Requirements

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