Report No.: FHWA-KS-14-15 ▪ FINAL REPORT ▪ March 2015

Surface Resistivity as an Alternative for Rapid Chloride Permeability Test of Hardened Concrete

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Kansas Department of Transportation
Bureau of Research

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1 Report No. FHWA-KS-14-15	**2 Government Accession No.**	**3 Recipient Catalog No.**
4 Title and Subtitle Surface Resistivity as an Alternative for Rapid Chloride Permeability Test of Hardened Concrete		**5 Report Date** March 2015 **6 Performing Organization Code**
7 Author(s) Andrew Jenkins, E.I.T.		**7 Performing Organization Report No.**
9 Performing Organization Name and Address Kansas Department of Transportation Bureau of Research 2300 SW Van Buren Topeka, Kansas 66611-1195		**10 Work Unit No. (TRAIS)** **11 Contract or Grant No.**
12 Sponsoring Agency Name and Address Kansas Department of Transportation Bureau of Research 2300 SW Van Buren Topeka, Kansas 66611-1195		**13 Type of Report and Period Covered** Final Report **14 Sponsoring Agency Code**
15 Supplementary Notes For more information write to address in block 9.		

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Testing for surface resistivity was set up to evaluate the correlation of surface resistivity with RCP and boil tests, the effect of loss of saturation on the sample, and the repeatability of surface resistivity testing. Results indicate a strong relationship (R-squared value of 0.84) between 28-day surface resistivity and 56-day C1202 RCP testing. Results also correlate well to a mathematical relationship derived through Ohm's Law. Surface resistivity did not have a strong relationship (R-squared value of 0.37) with C642 boil testing. Cylinders were cast to evaluate the effect of saturation levels and differential sample drying. Cylinders were allowed to dry for varying lengths of time at different ages. Results indicated that allowing the samples to dry, regardless of the length of drying time and the age at which the samples were drying, increased the surface resistivity results by an average of 15%. Through the course of this study, including all samples tested, the standard deviation and coefficient of variation on any given set of cylinders is 1.4 and 4.9%, respectively. If only samples used for the correlation of 28-day surface resistivity to 56-day RCP are used, the coefficient of variation is 4.2%. A cost-benefit analysis was performed to evaluate the monetary savings resulting from this research. A triennial analysis indicates a total cost savings by KDOT and contractors of approximately $980,000 and a cost-benefit ratio of 9.2.

As a result of this research, recommended specification limits have been developed for surface resistivity testing. As of January 2014, surface resistivity testing has been added to KDOT Standard Specifications as an alternate test method for concrete permeability.

17 Key Words Concrete permeability, Surface resistivity, Rapid Chloride Permeability, Volume of Permeable Voids, Materials testing		**18 Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service www.ntis.gov.	
19 Security Classification (of this report) Unclassified	**20 Security Classification (of this page)** Unclassified	**21 No. of pages** 39	**22 Price**

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A Report on Research Sponsored by

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TOPEKA, KANSAS

March 2015

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Abstract

Kansas experiences harsh winters that require frequent use of de-icing salts, making it critical to the long-term durability of concrete structures that the permeability is kept under control. Under current KDOT specification, the Rapid Chloride Permeability (RCP) test, as described in ASTM Standard C1202 (2012), or the Volume of Permeable Voids method, described in ASTM Standard C642 (2013), more commonly known as the boil test, must be performed to evaluate concrete permeability. Surface resistivity testing was investigated as an alternative to these tests.

Testing for surface resistivity was set up to evaluate the correlation of surface resistivity with RCP and boil tests, the effect of loss of saturation on the sample, and the repeatability of surface resistivity testing. Results indicate a strong relationship (R-squared value of 0.84) between 28-day surface resistivity and 56-day C1202 RCP testing. Results also correlate well to a mathematical relationship derived through Ohm's Law. Surface resistivity did not have a strong relationship (R-squared value of 0.37) with C642 boil testing.

Cylinders were cast to evaluate the effect of saturation levels and differential sample drying. Cylinders were allowed to dry for varying lengths of time at different ages. Results indicated that allowing the samples to dry, regardless of the length of drying time and the age at which the samples were drying, increased the surface resistivity results by an average of 15%.

Through the course of this study, including all samples tested, the standard deviation and coefficient of variation on any given set of cylinders is 1.4 and 4.9%, respectively. If only samples used for the correlation of 28-day surface resistivity to 56-day RCP are used, the coefficient of variation is 4.2%.

A cost-benefit analysis was performed to evaluate the monetary savings resulting from this research. A triennial analysis indicates a total cost savings by KDOT and contractors of approximately $980,000 and a cost-benefit ratio of 9.2.

As a result of this research, recommended specification limits have been developed for surface resistivity testing. As of January 2014, surface resistivity testing has been added to KDOT Standard Specifications as an alternate test method for concrete permeability.

Acknowledgements

Special thanks are extended to Kansas Department of Transportation (KDOT) Research personnel Rodney Montney, Dave Meggers, and Jennifer Distlehorst for their guidance and support during the course of the study and for their review of this report. Thanks are extended to Nathan Dormer, Luke Rosdahl, and Geary Beeson for their efforts in training personnel, and completing the testing and data collection. Thanks are also extended to KDOT District Materials Lab personnel for their participation in the data collection.

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Chapter 1: Introduction

1.1 Background

Concrete is a widely used transportation construction material. To predict and regulate the performance of concrete, compressive strength and durability are widely considered the two most important characteristics. Kansas Department of Transportation (KDOT) specifies that concrete mixtures must meet minimum compressive strength requirements and several different durability requirements, depending on the application. These durability requirements include aggregate source, air void content and structure, and permeability testing.

1.2 Problem Statement

Kansas experiences harsh winters that require frequent use of de-icing salts on the roadways. Also, considering the significant number of freeze-thaw cycles Kansas undergoes, it is critical to the long-term durability of concrete structures that the permeability is kept under control. That is, it is important to lower the permeability in order to reduce the amounts of water and chlorides entering and deteriorating the concrete and corroding the reinforcement. The Rapid Chloride Permeability (RCP) test as described in ASTM Standard C1202 (2012), "Standard test method for electrical indication of concrete's ability to resist chloride ion penetration," is currently the only "rapid" test to determine the permeability of a concrete specimen. C1202 is a multiple day test with the chloride penetration portion of the test lasting six hours. There is a need for a faster, more efficient method of determining the permeability of a concrete mixture. Additionally, under current KDOT specification, the RCP test is performed at 56 days of age, requiring an additional 28-day waiting period beyond the 28-day compressive strength testing. KDOT also allows concrete permeability to be tested by ASTM Standard C642 (2013), "Standard test method for density, absorption, and voids in hardened concrete," more commonly known as the "boil test." While C642 does benefit from being a 28-day test, as well as its ease, simplicity, and cost effectiveness in comparison to C1202, there is a lack of acceptance for this test procedure from the contractor community due to its sensitivity to changes in the concrete mix design.

1.3 Objectives

The objectives of this study were to evaluate four primary items: the correlation of surface resistivity with RCP and boil tests, the change in surface resistivity over time, the effect of loss of saturation on the sample, and the repeatability of surface resistivity testing. Correlations of surface resistivity to RCP and boil testing are to provide an additional option for permeability testing and/or to replace the RCP and boil tests with the resistivity testing in KDOT Specifications. While surface resistivity testing was completed at a range of sample ages for this study, the primary objective was to provide information for 28-day surface resistivity testing in order to limit the wait time with the current 56-day RCP test. This study also served to develop precision and repeatability values for surface resistivity testing. The newest balloted version of AASHTO Standard TP95-11 (2011) will also contain a precision statement.

1.4 Scope

Several correlations were made to determine the most effective application of surface resistivity testing for KDOT. Since one key objective is to provide surface resistivity testing earlier than 56 days, 28-day Surface Resistivity Measurements (SRMs) will be correlated with KDOT's two currently accepted tests: 28-day boil testing and 56-day RCP testing. In an effort to further describe the relationship between surface resistivity and RCP, 14-, 28-, 56-, and 90-day SRMs were correlated to same age RCP test results (14, 28, 56, and 90 days). Additionally, SRM values were tracked and analyzed over a one year period in order to describe the long term characteristics of surface resistivity. Analysis was also performed to determine the effect of saturation loss from the samples at varying time intervals to determine the resulting effect on SRMs. Mix designs were tracked and evaluated for repeated testing and consistency.

1.5 Literature Review

Surface resistivity has successfully been correlated to RCP in the past. Chini, Muszynski, and Hicks (2003) provided a very comprehensive evaluation. They evaluated seven of the Florida Department of Transportation's (FDOT) concrete classifications. Each class of concrete is designated for a different application. A total of 500 sets of samples were tested as part of the study with the highest number of samples coming from two of the most common classifications. The tests were performed on samples of the same age at 28 and 91 days. The results of the study indicated that different permeability requirements, no matter the test method, should be considered for each classification. The study found a very strong correlation between RCP and SRM. The recommended surface resistivity ranges for low, moderate, and high permeability concrete presented in the report are those which were adopted by AASHTO and placed in AASHTO Standard TP95-11 (2011), "Standard method of test for surface resistivity indication of concrete's ability to resist chloride ion penetration."

Hamilton, Boyd, and Vivas (2007) completed a study comparing several concrete permeability tests including surface resistivity, RCP, and salt ponding (AASHTO Standard T259, 2012). They showed a good correlation between all testing that was performed. They also showed no significant difference between curing SRM samples in a 100% humidity (moist cure) environment and lime-water storage tanks, even though AASHTO requires a correction factor of 1.1 for samples stored in lime-water.

Rupnow and Icenogle (2011) performed a study comparing RCP to surface resistivity with several different mixtures, each with several different water/cement ratios. They also compared the tests over a wider range of ages; of note is the 28-day surface resistivity versus the 56-day RCP. It was concluded that there existed a strong relationship between the two tests across all tested ages.

Chapter 2: Methodology

2.1 Current KDOT Permeability Testing

As of 2013, KDOT specifications require all concrete for pavement and structures to meet permeability requirements. The current requirements are presented in Table 2.1, which shows the maximum values allowed for a 56-day Rapid Chloride Permeability (RCP) test (ASTM Standard C1202, 2012; AASHTO Standard T277, 2011) and a 28-day Volume of Permeable Voids (boil) test (KT-73 Kansas Test Method, 2012; ASTM Standard C642, 2013) for standard air entrained concrete and silica fume modified concrete. Concretes with supplementary cementitious materials (SCMs) other than silica fume must meet the requirements for standard air entrained concrete. KDOT specifications only require that permeability results be submitted as part of the mix design approval process and a single field verification test (KDOT, 2007).

Table 2.1: Current KDOT Concrete Permeability Requirements

	56-Day RCP Maximum	28-Day Boil Maximum
Standard Air Entrained Concrete	3500 Coulombs (C)	12.5%
Silica Fume Concrete (LPC)	1000 C	9.5%

2.2 Surface Resistivity

Surface resistivity testing was performed following KT-79 Kansas Test Method (2014), "Surface resistivity indication of concrete's ability to resist chloride ion penetration," which is based on the provisional AASHTO test method AASHTO Standard TP95-11 (2011). Both test methods call for the surface resistivity to be measured with a Wenner array. A Proceq Resipod with a probe spacing of 1.5 inches was used for this study. KT-79 calls for the SRMs to be taken at a sample age of 28 days on 100% saturated 4x8 inch cylindrical samples. At this time, KT-79 does not allow for SRMs to be performed on 6x12 inch samples, and it stipulates that readings are to be taken no earlier than 27 days and no later than 32 days. Eight readings are taken on each cylinder and three cylinders are tested for each mix or design, for a total of 24 SRMs per mix or design. These readings are averaged to report a single resistivity measured in kilohm-centimeters (kΩ-cm). A correction factor of 1.1 is applied to results from samples that are cured in lime-water tanks. KT-79 also describes the specimen curing requirements for both cast cylinders and cores taken from in situ concrete pavement. Limited testing of cores was performed during this study. For most cases in which cores were tested, the reported value was not an average of three cores. This is due to KDOT's requirements for coring, in which the number of cores taken is dependent on the volume of concrete pavement placed, resulting in a variable number of cores. Testing of in situ concrete and cores will be addressed further in future research.

2.3 Testing Setup

As previously discussed, testing for surface resistivity was set up to evaluate the correlation of SRMs with RCP and boil tests, the change in SRM over time, the effect of loss of saturation on the sample, and the repeatability of SRM. This study was not designed to specifically evaluate surface resistivity for varying mix designs. Therefore, testing commenced initially on concrete samples KDOT Materials Test Unit and KDOT Research were already receiving for compressive strength and permeability testing. These samples consisted of 28-day strength compressive samples and 56-day RCP samples. The information from these samples comprises the majority of the SRM vs. RCP/Boil data and the repeatability data. In order to analyze the change in SRM over time, SRM samples were cast from batches for other ongoing KDOT Research studies. An additional test was performed entirely for the evaluation of the effect of loss of saturation on surface resistivity results. As mentioned, some testing was performed on cores to determine the feasibility of surface resistivity acceptance testing for in situ concrete. In order to help facilitate the collection of data, primarily the testing of cores and boil samples, each of KDOT's six district laboratories purchased a resistivity meter in the spring of 2012. For testing at the central laboratory, all samples were cured in a moist room in accordance with ASTM Standard C511 (2009), "Standard specification for mixing rooms, moist cabinets, moist rooms, and water storage tanks used in the testing of hydraulic cements and concretes." The district laboratories stored samples in lime-water storage tanks, also in accordance with ASTM Standard C511. Note that one set of samples is defined as three samples from the same batch of concrete.

Chapter 3: Results

3.1 Same Age SRM vs. RCP

In order to correlate SRM to RCP, it was necessary to evaluate the relationship between the two tests on the same samples at the same age. The majority of the data represented here is from samples at 56 days of age. This is due to the fact that current KDOT specification calls for RCP testing to be performed at 56 days of age, therefore resulting in a larger number of samples with available RCP data. Of the 343 sets of same-age samples, 302 sets are 56-day SRM vs. 56-day RCP. Additionally, 10 sets are 14-day SRM vs. 14-day RCP, 13 sets are 28-day SRM vs. 28-day RCP, and 18 sets are 90-day SRM vs. 90-day RCP. All of the data for RCP testing other than 56-day testing was obtained by casting additional cylinders as part of other ongoing Research studies. Figure 3.1 illustrates the correlation of SRM with RCP for all age pairings. The correlation found by KDOT Research is represented by the black power curve and the corresponding equation. This can be compared to the AASHTO correlation presented in AASHTO Standard TP95-11 (2011) which is plotted in red. Note that the R^2 value for the same-age pairings of SRM vs. RCP is 0.86, indicating there is a very strong correlation between these test results. These values also correlate well with the AASHTO standard.

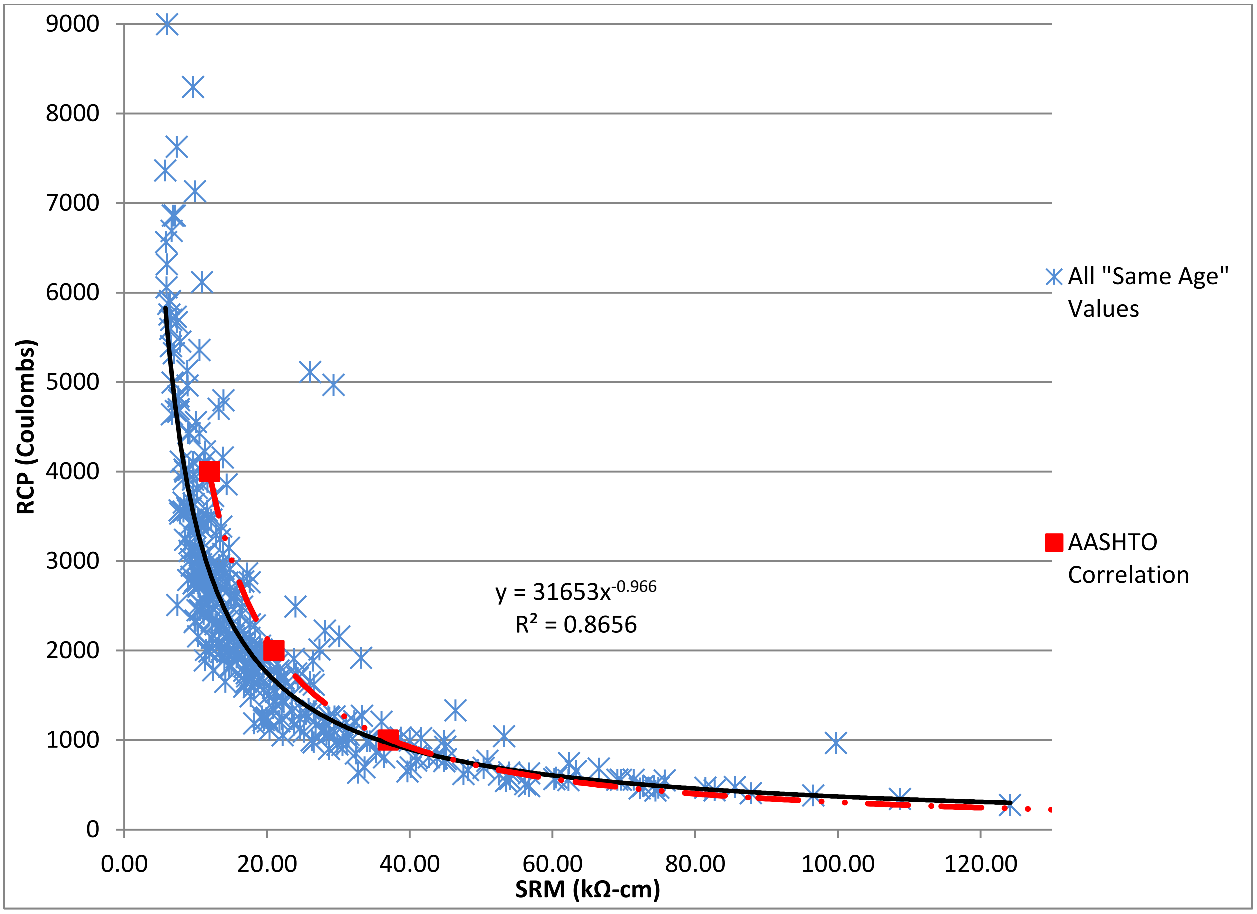

Figure 3.1: SRM vs. RCP Correlation for All Same-Age Pairings

3.2 28-Day SRM vs. 56-Day RCP

The desire to perform resistivity testing at 28 days required a correlation be developed between 28-day SRM and the current standard of 56-day RCP. This data set is not quite as large, at only 134 sets of samples due to the non-routine need to test the 56-day RCP samples for resistivity at 28 days. Initially, data was only available for samples that were either cast by Research personnel, allowing staff access to the samples at 28 days, or on RCP samples which were submitted to the lab before they reached 28 days of age, which was not common practice. However, in the spring of 2012, each of KDOT's six district materials laboratories purchased a surface resistivity meter and began testing for resistivity on the RCP samples at 28 days of age, prior to the submission of the samples to the central lab for RCP testing, which greatly increased the sample size. Figure 3.2 presents this data with the correlation represented by the black line.

In this case, the R^2 value is slightly lower at 0.84, and indicates that there is a strong relationship between 28-day SRM and 56-day RCP.

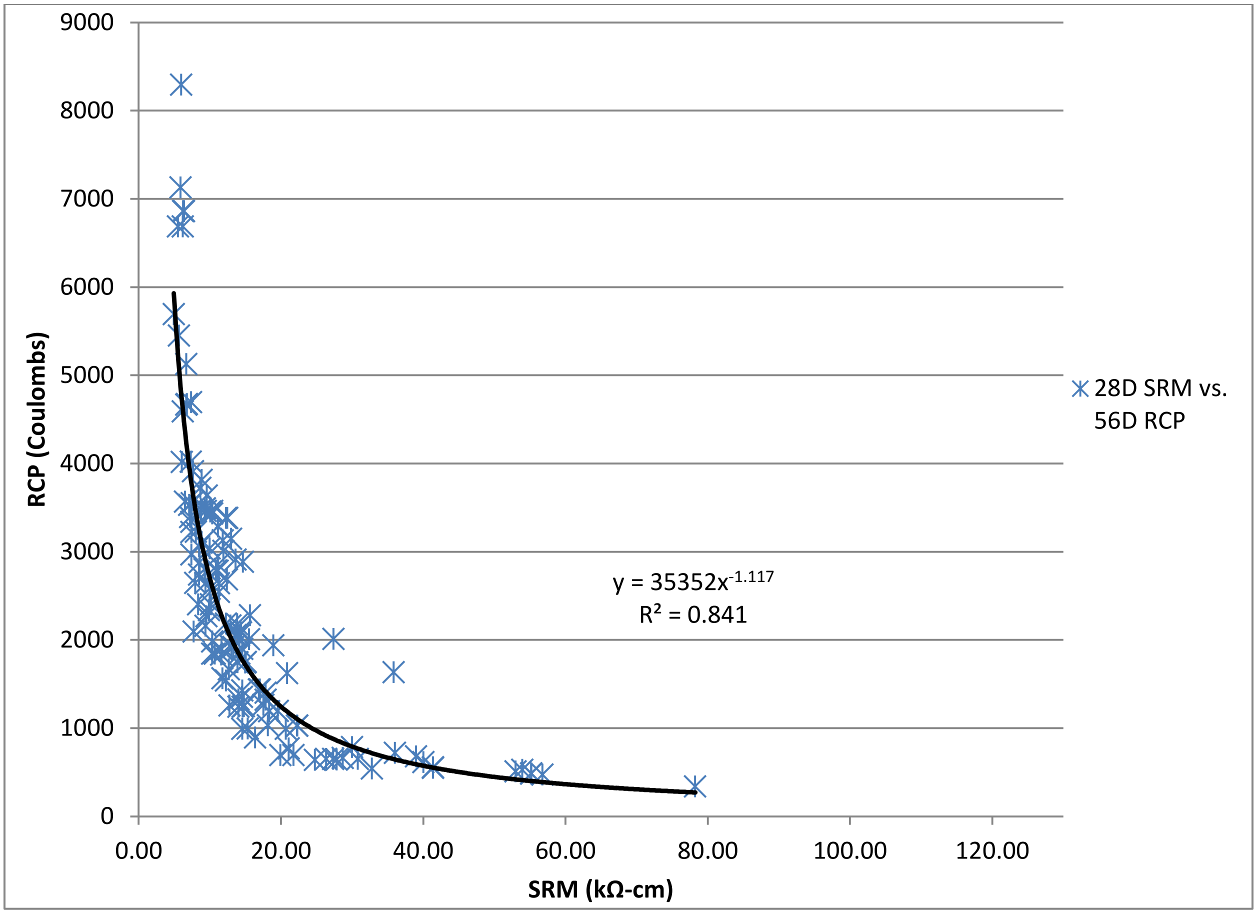

Figure 3.2: 28-Day SRM vs. 56-Day RCP Correlation

Additionally, a mathematical relationship between the RCP test and the surface resistivity test was developed. This relationship is based on the general formula for resistivity presented in Equation 3.1.

$$\rho = 2\pi a \frac{V}{I}$$ **Equation 3.1**

Where:

ρ = resistivity, kΩ-cm
a = probe spacing, cm
V = voltage, kilovolts
I = current, amps

To develop the relationship between surface resistivity and RCP, the current, I, was derived from the coulomb values (based on the six hour test length) obtained from the RCP, and used along with the RCP voltage (60 V). Also note that the diameter correction applied to the coulomb result in Section 11.2 of ASTM Standard C1202 (2012) must be taken back out of the RCP result that is entered into this equation. The constant, K, takes into account the voltage, V, the length of the RCP test in seconds, and the diameter correction from the RCP based on a 4-inch diameter sample. The final equation is presented in Equation 3.2.

$$\boldsymbol{\rho = 2\pi a\left(\frac{K}{RCP}\right)}$$ **Equation 3.2**

Where:
ρ = resistivity, kΩ-cm
a = probe spacing, cm
K = constant = 1139.06 kV*s;
RCP = Coulomb value from ASTM C1202

This relationship was developed for 28-day SRM vs. 56-day RCP, and is presented in Figure 3.3 along with the power curve for KDOT's data presented in Figure 3.2. In addition, the plot shows the power curve for the same testing set-up from Rupnow and Icenogle (2011). It can be noted that the data derived from the mathematical relationship and that from Rupnow and Icenogle correlate very well with KDOT's experimental results.

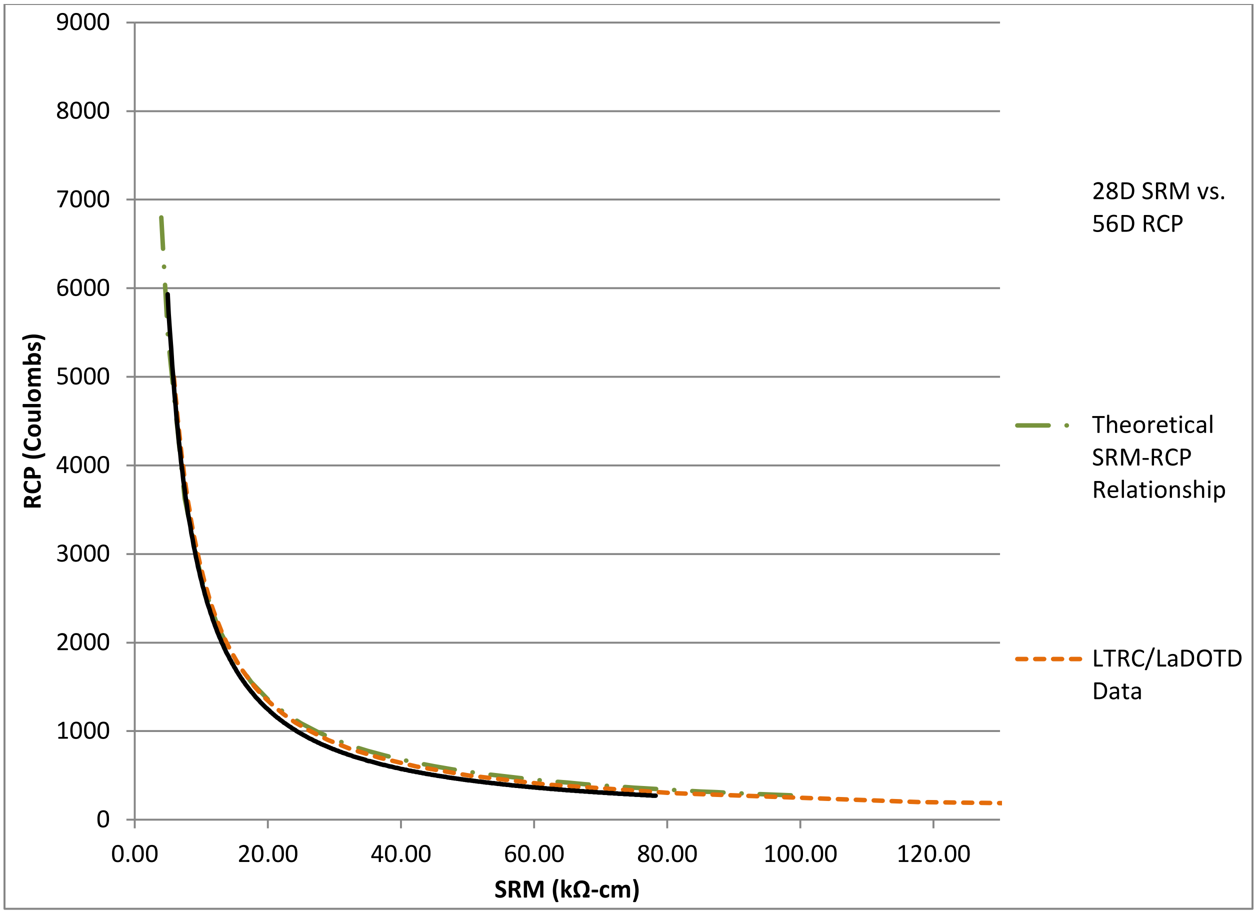

Figure 3.3: 28-Day SRM vs. 56-Day RCP with Theoretical Relationship and Louisiana Department of Transportation and Development (LaDOTD) data

3.3 28-Day SRM vs. 28-Day Boil

Since KDOT currently allows the use of ASTM Standard C642 (2013), the boil test, for mix design approval, it was necessary to evaluate the correlation between 28-day SRM and 28-day boil testing. The collected data consisted of 101 sets of samples with the majority of both resistivity and boil testing being completed at each of KDOT's District materials laboratories. Figure 3.4 presents the correlation of 28-day SRM vs. 28-day boil testing. The R^2 value for this correlation is 0.37. This indicates that there is not a strong correlation between the two tests. The weak correlation was not surprising, due to the fact that, while the tests are used to estimate concrete permeability, they are measuring different physical properties. The surface resistivity test is measuring the current flow through the concrete, while the boil test is measuring the volume of permeable voids. Additionally, since SRM testing must take place on a full 4x8 inch cylinder, SRM testing must occur at an age of 21 days, before the samples are processed for boil testing. This testing at a significantly different age may also contribute to the weak correlation.

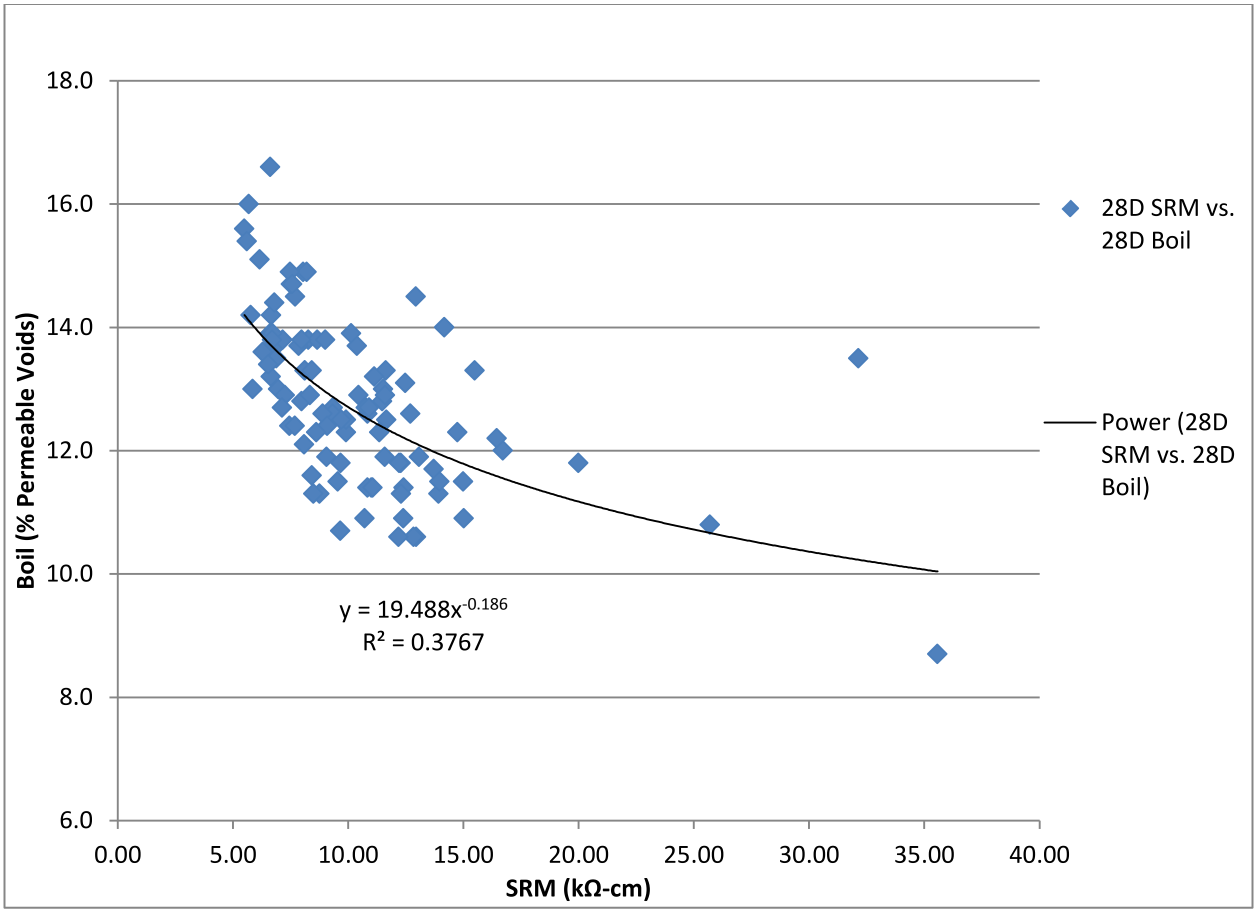

Figure 3.4: 28-Day SRM vs. 28-Day Boil Correlation

3.4 SRM Over Time

An attempt was also made to characterize surface resistivity of concrete over time. To study this relationship, samples were cast specifically for resistivity testing and were tested for 365 days. In most cases, the samples were added to batches of concrete prepared for other research projects, providing for a wide range of mix designs as shown in Figure 3.5. For this study, the samples were read every weekday for the first seven days of age, and then once every seven days on days 7, 14, 21, 28, 35, 42, 49, 56, 63, 70, 77, 84, and 90. After the reading at day 90, the samples were read at days 120, 150, 180, and 365. Figure 3.5 only presents the data up to day 90. The readings indicate the bulk of the permeability properties as measured by resistivity were established within 28 days of age. In most cases, there is no significant benefit to wait until 56 days of age to take resistivity readings. The exception to this is sample 12-0341, which is a class F fly ash and silica fume ternary concrete. The positive linear slope indicates there is significant permeability reduction over time, likely due to the delayed property gain from the use of supplemental cementitious materials (SCMs), and testing at a later date may produce more accurate "actual" permeability results. However, two additional concretes presented in Figure 3.5 also contained SCMs and do not show the same trend, indicating further research would be needed to evaluate the development of resistivity with time in concretes that contain SCMs.

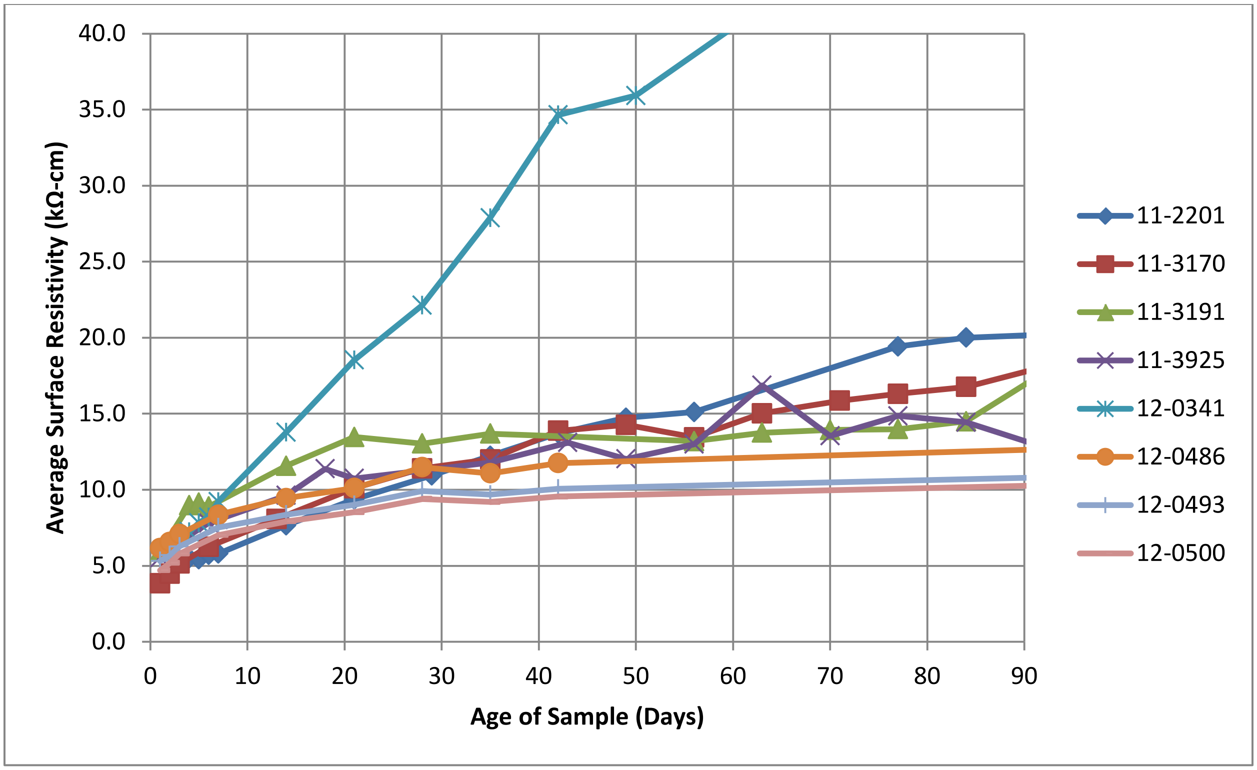

Figure 3.5: SRM Reading over 90 days

3.5 Differential Drying

A key aspect of surface resistivity testing is the saturation of the samples when they are tested. It was observed that when a sample was allowed to dry to any degree, the SRM values increased. This is of concern, since it is therefore possible to manipulate the test by letting the samples dry out prior to testing, artificially giving the higher and more desirable SRM values. To accurately investigate this effect, it was necessary to cast a large number of samples, dry them at various intervals, and compare to a control set. The mix design used for this testing can be found in Table 3.1. Due to the large number of samples required, two batches were mixed, each with its own set of control samples. The readings were then normalized to the control samples from the first batch in order to compare to other batch samples. Overall, samples were allowed to dry according to the schedule in Table 3.2. Note that the cast date is day “0” and the day the samples were demolded is day “1.” When the samples were drying, they were stored at 73±3 °F and 50±4% relative humidity according to Section 11.1.2 Air Storage of ASTM Standard C157 (2008), “Standard test method for length change of hardened hydraulic-cement mortar and concrete”; otherwise, samples were stored in a moist room per ASTM Standard C511 (2009). All samples had SRMs performed at 28 days of age.

Table 3.1: Differential Drying Mix Design

Mix Design Property	Value
Design CF, lbs/yd^3	540
Design W/C	0.42
Design Air	6.5%
Coarse – Fine Aggregate Ratio	60/40
Cement	Type I/II
SCMs present	25% Class C Fly Ash

Table 3.2: Drying Schedule for Evaluation of Loss of Saturation on Surface Resistivity

Day Drying	Sample Set #
N/A	Control
Day 1	1
Days 1-2	2
Days 1-3	11
Days 1-5	3
Days 1-6	15
Days 2-4	12
Days 4-6	13
Days 6-8	14
Days 7-9	4
Days 7-13	5
Days 14-16	6
Days 14-20	7
Days 21-23	8
Days 21-24	9
Days 21-28	10
Days 1-27	16

The schedule was created in order to determine if there was a difference between the length of time the samples were allowed to dry and the time-frame during which they were drying. Key times, such as the day of demolding (day 1), days 7-9, 14-21, and 21-23, were all chosen because they are likely times at which the samples could be transported, and therefore subject to drying conditions. Figure 3.6 presents the effects of drying. Note that the single SRM average taken at 28 days is plotted versus the time frame at which the sample was drying (e.g., set #10 had a 28-day SRM of 12.4 kΩ-cm and it was drying from days 21-28; the plot shows a value of 12.4 kΩ-cm from days 21-28).

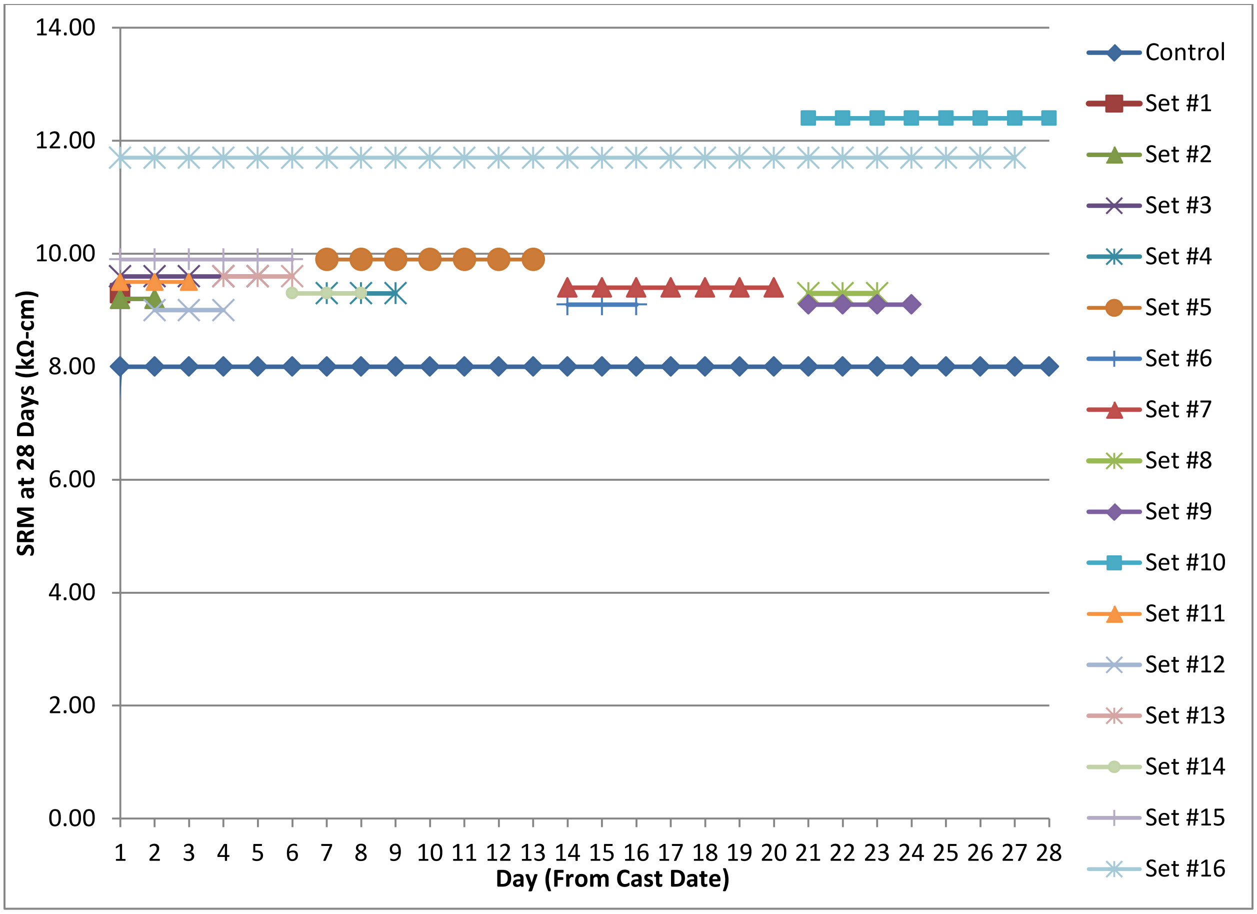

Figure 3.6: Effects of Differential Drying on Surface Resistivity Measurements

With the exception of set #10, in which the samples were dry on day 28 at the time of testing, and set #16, in which the samples were drying from days 1-27, there was a relatively consistent increase in the SRM value for all sets, regardless of when or for how long they were allowed to dry. The values ranged from a 14% increase to a 24% increase, with an average of an 18% increase over the control. It should be noted that AASHTO Standard TP95-11 (2011) and KT-79 Kansas Test Method (2014) require the samples to be in a 100% relative humidity moist cure environment for the entire 28-day curing period.

3.6 SRM Repeatability

Analysis was initially performed on the readings from any given set of samples to determine the variability in measurements. The standard deviation and coefficient of variation (CV, expressed in percent) was calculated for each set of samples. For the 1,501 sets of samples included in this analysis, the average standard deviation was found to be 1.4. The average CV was found to be 4.9%. A total of 31% of the samples (462 sets) had a CV higher than the average of 5%. A total of 4.1% (61 sets) had a CV higher than 10%. It should be noted that these values include all samples tested, including those tested from 14 to 90 days of age and several samples which underwent non-standard curing conditions, such as cores (see Section 3.7) and field cured samples. If only samples which underwent standard curing are considered (1,249 sets), 23% have a CV greater than 5%. Of the samples used for the 28-day SRM vs. 56-day RCP correlation (134 sets), the average CV was found to be 4.2%, and 23% of the sets (31) had a CV higher than 5%.

A round robin was conducted as part of a training class when each of the districts received their resistivity meter. There were 7 sets of samples (21 total cylinders), with each set being tested by a combination of up to three different operators and their meters. One set was only tested by the central laboratory and two sets of samples were only tested twice. This resulted in a standard deviation for each set ranging from 0.6-1.2 and the CV ranging from 2.9-5.4%. Since all samples were from the same batch, it allowed comparisons across all readings. This resulted in 17 sets of readings for the same batch of concrete. Overall, the standard deviation was 1.0 and the CV was 4.8%. The new version of AASHTO Standard TP95-11 (2011) that was sent to ballot in late 2013 had an allowable CV of 12.5%.

Results were also tracked by mix design. SRMs for mix designs with at least two results were plotted. The majority of this testing took place on strength samples or a combination of strength and RCP/boil samples, as it is not common to submit samples more than once for RCP or boil testing. The data here is not nearly as robust or consistent. Two things should be noted. First, these SRMs represent field concretes from different batches throughout the project. Some variability is expected. Second, since the majority of the samples were submitted to a work unit other than Research, for tests other than surface resistivity, the lack of consistency in values could also be a result of different handling procedures, e.g., compressive strength samples must be dried for sulfur caps to be applied. The balloted version of AASHTO Standard TP95-11 (2011) contained a percent relative standard deviation component that may resolve some of the handling consistency issues. Figure 3.7 presents the SRM values versus the number of times that mix design has been tested for District One samples. A total of 82 unique mix designs were tested for District One, so Figure 3.7 presents only mix designs which were tested at least four times. Table 3.3 also presents the high, low, average, standard deviation, and coefficient of variation for the mix designs presented in Figure 3.7. Figures for Districts Two, Four, and Five can be found in the Appendix; Districts Three and Six did not have enough samples tested to report. It can be seen that several mix designs show significant variability that is likely not a result of sample handling, but rather a significant change in the concrete itself.

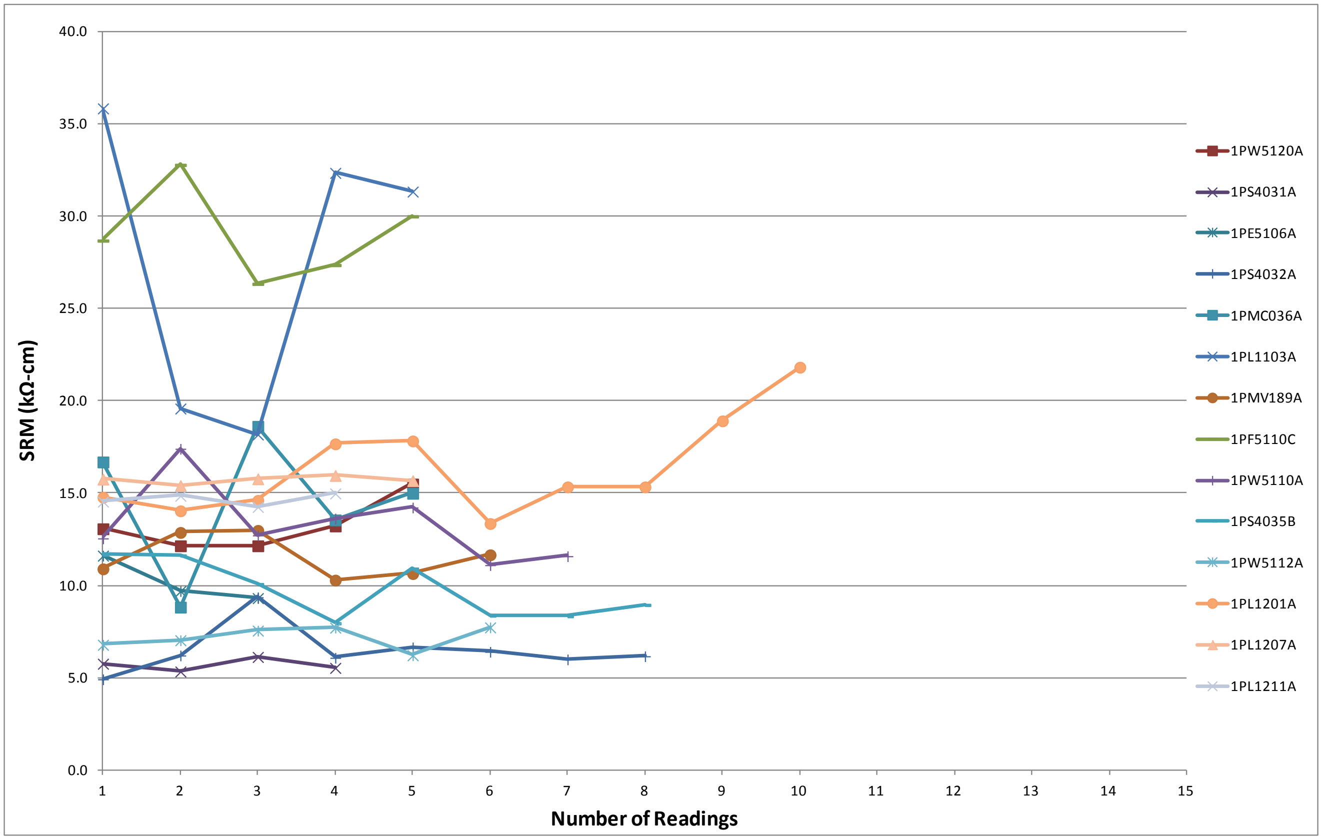

Figure 3.7: District One Mix Designs Measured for Surface Resistivity

Table 3.3: Reported Values for District One Mix Designs

Mix Design	Highest SRM, kΩ-cm	Lowest SRM, kΩ-cm	Average SRM, kΩ-cm	Standard Deviation	CV, %
1PW5120A	15.51	12.17	13.3	1.23	9.3
1PS4031A	5.37	6.15	5.7	0.34	5.9
1PS4032A	9.38	4.95	6.5	1.27	19.6
1PMC036A	18.64	8.85	14.6	3.71	25.5
1PL1103A	35.85	18.20	26.4	7.63	28.9
1PMV189A	13.00	10.31	11.6	1.15	9.9
1PF5110C	32.79	26.35	29.0	1.70	17.6
1PW5110A	17.42	11.13	13.3	1.10	15.7
1PS4035B	11.69	7.98	9.8	1.53	15.7
1PL1207A	15.98	15.43	15.7	0.20	1.3
1PL1211A	15.00	14.28	14.7	0.33	2.2
1PS4045C	15.41	9.68	12.6	2.90	23.0

3.7 Testing of Core Samples

After each of the districts purchased a surface resistivity meter, district personnel tested cores from pavements that were submitted for thickness and strength verification. In addition to the contractor's quality control testing, KDOT currently tests one core per lot of concrete for compressive strength. The SRM test is conducted on the compressive strength core. Per KDOT Specifications (KDOT, 2007), a lot is defined as the surface area of mainline concrete placed in a single day. There are adjustments to the number of lots depending on whether a single day's worth of paving is less than 1000 ft^2 (combine two days of paving into a single lot) or greater than 6000 ft^2 (contractor may choose to split into two equal lots). Therefore, a significant number of compressive strength cores are rarely obtained for KDOT at any given time, and never are a set of three cores obtained from a single location. In addition to the limited number of samples, cores obtained for these purposes are obtained according to KT-49 Kansas Test Method (2012), "Method for obtaining and testing drilled cores from PCCP and precast girders." This test method requires samples to be stored in their saturated surface dry (SSD) condition after coring, but does not permit the samples to be placed in curing environment that would be found in ASTM Standard C511 (2009).

Given the limited sample size for any single location and/or batch of concrete, and given the difference in the curing conditions currently used for cores, the surface resistivity data obtained was highly variable. The values were unable to be used in any analysis or evaluation. Solutions are discussed in Section 4.2.

3.8 Cost Benefit Analysis

A cost-benefit analysis was performed to evaluate the monetary savings resulting from this research. KDOT standard practice is to perform cost-benefit analyses on a triennial basis. The triennial analysis indicates that, assuming 100% replacement of KDOT's current RCP and boil testing with surface resistivity testing, KDOT will realize a monetary savings of approximately $205,000. This is based on an average number of 350 RCP tests and 240 boil tests run each year. Table 3.4 presents the estimated triennial cost savings for KDOT.

Table 3.4: Triennial Benefit Analysis of Permeability Tests for KDOT

Test	Number of Tests	Number of Hours Required	Technician Hourly Wage, $	Total Cost, $	Cost Per Test, $
RCP	350	2800	$18.00	$50,400.00	$144.00
Boil	240	1200	$18.00	$21,600.00	$90.00
SRM	590	197	$18.00	$3,540.00	$6.00
			Yearly Benefit	$68,460.00	
			Triennial Benefit	$205,380.00	

It was assumed that an average RCP requires eight hours of labor, the average boil test requires five hours, and the average surface resistivity test requires 0.33 hours (or 20 minutes). The total cost was determined by taking the technician hourly wage times the number of hours required. Note that these costs do not include the cost of the RCP or SRM equipment. The savings was determined by taking the difference between the total SRM cost and the sum of the total RCP and boil costs.

The triennial analysis for contractors is presented in Table 3.5. This analysis makes the conservative assumption that the same numbers of tests are run. It is also assumed that the contractor uses an independent laboratory for all testing at per-test rates of $600.00 (RCP), $350.00 (boil), and $60.00 (SRM) per set of three cylinders (values obtained from local independent laboratory). Based on this analysis, the contractor would realize a triennial savings of approximately $775,000.

Table 3.5: Triennial Benefit Analysis of Permeability Tests for Contractor

Test	Number of Tests	Number of Hours Required	Cost Per Test/Hourly Wage, $	Total Cost, $	Cost Per Test, $
RCP	350	-	$600.00	$210,000.00	$600.00
Boil	240	-	$350.00	$84,000.00	$350.00
SRM	590	-	$60.00	$35,400.00	$60.00
			Yearly Benefit	$258,600.00	
			Triennial Benefit	$775,800.00	

The total triennial benefit for the project is approximately $980,000. The cost of implementation is approximately $106,000, which includes approximately $81,000 in research costs and $25,000 in equipment costs. The estimated triennial cost-benefit ratio for KDOT is 1.9. The total estimated triennial cost-benefit ratio for KDOT and the contractor is 9.2, a significant portion of which KDOT would likely realize through the low bid process. This analysis indicates significant savings by switching to the surface resistivity testing. Refer to Chapter 4 for additional recommendations.

Chapter 4: Conclusions and Recommendations

4.1 Correlation to the RCP

The testing performed indicates surface resistivity was strongly correlated to the RCP test. It can also be confidently said that 28-day surface resistivity can be substituted for 56-day RCP testing. Table 4.1 lists the AASHTO RCP and surface resistivity classifications along with the 28-day SRM vs. 56-day RCP values from KDOT's testing, as well as the values from the derived theoretical relationship. The KDOT RCP design specification values and their equivalent AASHTO and KDOT surface resistivity values are also shown. Again, note that all of the AASHTO values are higher than the KDOT values. This difference is likely a result of two factors. First, it should be noted that the values presented by AASHTO are comprised of 28- and 90-day tests. The second factor is a result in a procedural difference in the surface resistivity testing. The values given in the AASHTO report are from the report by Chini et al. (2003). The test method used in that study differs in one significant area from the KDOT and AASHTO test methods. The key section to note is "Chapter 3: Methodology: Surface Resistivity Test" where it is stated that the samples "were removed from the holding tank in the morning and allowed to surface air dry. The time allotment for surface drying was not carefully monitored." The KDOT and AASHTO test methods require only that excess free surface moisture be blotted off immediately before testing. The KDOT sample drying results (Section 3.5 of this report) show that drying at any stage of the curing process increases resistivity. Thus, it can be reasonably deduced that the difference in procedure is a key reason for the difference in the correlation between values. Additionally, the data from the Louisiana Department of Transportation and Development (LaDOTD) and the theoretical relationship developed (Figure 3.3) correlate very strongly to each other and to the data obtained through KDOT's testing. Given that LaDOTD did not report any such drying time variation in their testing, this further supports the hypothesis that the difference between the data collected and the values presented by AASHTO can be attributed to allowing the samples to dry for an unspecified amount of time during testing in the case of Chini et al. As a result of these two factors, the information in Table 4.1 is presented only as a guide to point out that the values presented in AASHTO Standard TP95-11 (2011) should be evaluated on a case by case basis based on how surface resistivity testing is being implemented.

Table 4.1: AASHTO RCP and Surface Resistivity with KDOT Equivalent and KDOT Preliminary Surface Resistivity Design Values

Chloride Ion Permeability	RCP	Surface Resistivity		
	AASHTO Rapid Chloride Permeability Charge Passed (Coulombs)	AASHTO 4x8 Cylinder a = 1.5 in. (kΩ-cm)	KDOT 4x8 Cylinder a = 1.5 in. (kΩ-cm)	KDOT Theoretical values from Eqn. 3.2 a = 1.5 in. (kΩ-cm)
High	>4000	<12	<7.0	<6.8
Moderate	2000-4000	12-21	7.0-13.0	6.8-13.6
Low	1000-2000	21-37	13.0-24.3	13.6-27.2
Very Low	100-1000	37-254	24.3-191	27.2-272
Negligible	<100	>254	>191	>272
KDOT Standard Spec.	3500	13.0	8.0	-
KDOT Silica Fume Spec.	1000	37.5	24.0	-

4.2 Recommendations

Based on the results of this study, it is recommended that the design values for 28-day surface resistivity presented in Table 4.2 be implemented as a special provision as a supplement to, but not a replacement for, the current 56-day Rapid Chloride Permeability (RCP) test (ASTM Standard C1202, 2012; AASHTO Standard T277, 2011) or a 28-day Volume of Permeable Voids (boil) test (KT-73 Kansas Test Method, 2012; ASTM Standard C642, 2013). Based on KDOT's past experience, future goals, and in relation to permeability requirements from neighboring DOTs, it is also recommended this opportunity be taken to adjust KDOT's current permeability requirements. Lastly, due to a shift in philosophy, it is recommended that a third concrete permeability classification for specific full depth concrete bridge decks and new definitions of each classification be developed. Table 4.2 presents the recommended permeability requirement for each of the three permeability tests in each of the new permeability classifications. The definitions of each classification are presented as footnotes to Table 4.2.

There is a need to further investigate the effect of sample drying before wholesale transitions from RCP and Boil testing to SRM can be recommended. This also means that the total savings presented in the cost benefit analysis in Section 3.8 are not likely to be realized in the first few years. To realize the entirety of the savings, the RCP and boil tests would need to be removed from KDOT specifications, which is not being recommended in this report.

Table 4.2: Recommended KDOT Concrete Permeability Specifications

Permeability Classification	56 Day RCP (C) maximum	28 Day Boil Test (% volume perm. voids) maximum	28 Day Surface Resistivity (kΩ-cm) minimum
KDOT "SPC" Spec.[1]	3000	12.0	9.0
KDOT "MPC" Spec.[2]	2000	11.0	13.0
KDOT "LPC" Spec.[3]	1000	9.5	27.0

[1] "Standard Permeability Concrete" – Concrete paving, bridge deck, sub-deck, and all other structures
[2] "Moderate Permeability Concrete" – Full depth bridge decks when called out in plans
[3] "Low Permeability Concrete" – Bridge deck wearing surface

Future research would further investigate the effect of drying standard samples and also samples obtained from the in situ concrete structure, i.e., core samples. Every attempt will be made to address some of the issues discussed with cores in Section 3.7. Cores will be taken by Research personnel specifically for the purpose of surface resistivity testing, and various curing and saturation techniques will be evaluated for their effectiveness in obtaining SRM values that are more repeatable. Future research would also investigate the possible use of surface resistivity measurements on in situ concrete without the need to obtain core samples.

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Appendix

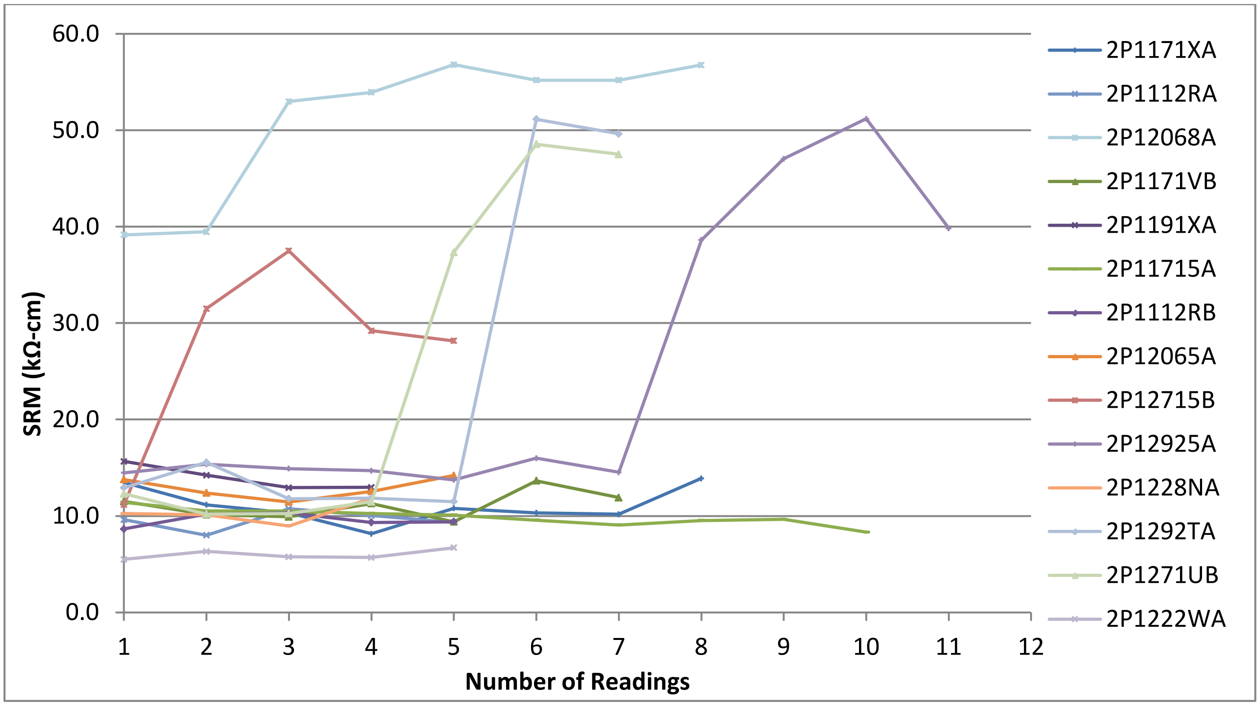

Figure A.1: District Two Mix Designs Measured for Surface Resistivity

Table A.1: Reported Values for District Two Mix Designs

Mix Design	Highest SRM, kΩ-cm	Lowest SRM, kΩ-cm	Average SRM, kΩ-cm	Standard Deviation	CV, %
2P1171XA	13.89	8.15	11.0	1.86	16.9
2P1112RA	10.74	8.00	9.5	1.02	10.6
2P12068A	56.82	39.15	51.2	7.45	14.5
2P1171VB	13.64	9.40	11.1	1.44	13.0
2P1191XA	15.66	12.93	13.9	1.29	9.2
2P11715A	11.42	8.31	9.9	0.87	8.8
2P1112RB	10.33	8.65	9.6	0.67	7.2
2P12065A	14.19	11.46	12.9	1.11	8.6
2P12715B	37.49	11.16	27.5	9.83	35.7
2P12925A	51.19	13.74	25.5	15.18	59.6
2P1228NA	11.84	8.96	10.3	1.18	11.5
2P1292TA	51.14	11.48	23.5	18.44	78.5
2P1271UB	48.55	10.20	25.4	18.23	71.8
2P1222WA	6.70	5.50	6.0	0.50	8.4

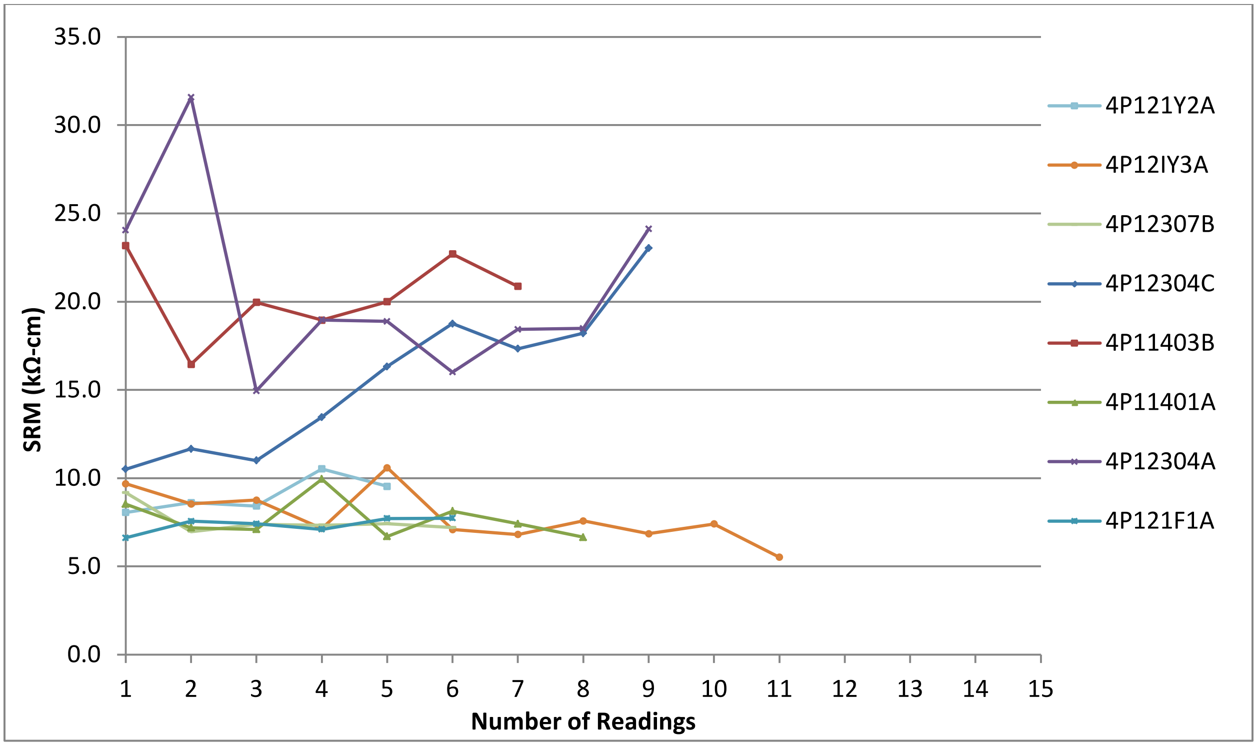

Figure A.2: District Four Mix Designs Measured for Surface Resistivity

Table A.2: Reported Values for District Four Mix Designs

Mix Design	Highest SRM, kΩ-cm	Lowest SRM, kΩ-cm	Average SRM, kΩ-cm	Standard Deviation	CV, %
4P121Y2A	10.52	8.05	9.0	0.99	11.1
4P121Y3A	10.59	5.52	7.5	1.37	18.3
4P12307B	9.17	6.97	7.6	0.80	10.5
4P12304C	23.03	10.50	15.6	4.22	27.1
4P11403B	23.18	16.45	20.3	2.28	11.2
4P11401A	9.94	6.66	7.7	1.11	14.5
4P12304A	31.57	14.95	20.6	5.15	25.0
4P121F1A	7.73	6.62	7.4	0.43	5.8

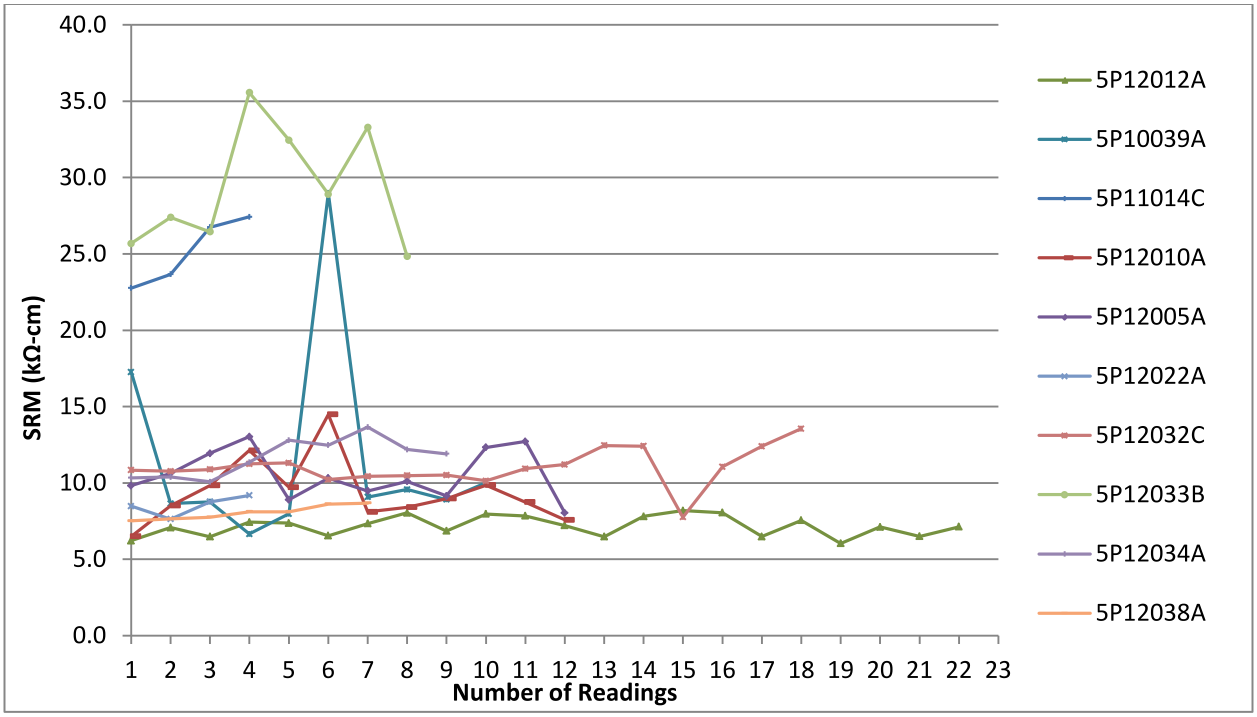

Figure A.3: District Five Mix Designs Measured for Surface Resistivity

Table A.3: Reported Values for District Five Mix Designs

Mix Design	Highest SRM, kΩ-cm	Lowest SRM, kΩ-cm	Average SRM, kΩ-cm	Standard Deviation	CV, %
5P12012A	8.19	6.04	7.2	0.65	9.1
5P10039A	28.99	6.66	11.6	6.74	58.2
5P11014C	27.43	22.76	25.2	2.28	9.1
5P12010A	14.49	6.50	9.4	2.12	22.6
5P12005A	13.03	8.04	10.5	1.62	15.4
5P12022A	9.19	7.64	8.5	0.65	7.7
5P12032C	13.55	7.76	11.0	1.23	11.1
5P12033B	35.57	24.85	29.3	3.96	13.5
5P12034A	13.66	10.34	11.7	1.24	10.6
5P12038A	8.68	7.52	8.1	0.46	5.7

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