Determining Concrete Chloride Permeability Rapidly and Effectively

Final Report

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16. Abstract

A study was conducted to determine if chloride permeability could be determined more quickly and efficiently. Two mixtures were selected by the Tennessee Department of Transportation (TDOT) Materials and Tests (M&T) Division: a TDOT Class D mixture with 20% Class F fly ash and an experimental mixture containing 35% Grade 120 slag and 15% Class F fly ash.

Five validation batches of each mixture were produced. The plastic and hardened properties of all validation batches of both mixtures met TDOT 604.03 Class D requirements. Subsequently, twenty batches of each mixture were produced for chloride permeability comparison. Rapid chloride permeability ((RCP) AASHTO T 277) was measured after 28 days of accelerated curing and also after 56 and 91 days of normal curing. Surface resistivity ((SR) AASHTO TP 95) was measured after 28 days of accelerated curing and also after 28, 56 and 91 days of normal curing. Additional data from other TTU studies was also used in the correlations and predictions. The correlation between SR and RCP was significantly different from the correlation based on AASHTO categories, but, on average, differed from AASHTO by less than 4%. Correlations between earlier and later age values of both SR and RCP were very strong ($R^2 > 0.9$) for both accelerated and normal moist curing.

The authors recommend that TDOT M&T:

1. Use SR instead of RCP for primarily logistical reasons.
2. Use normal curing rather than accelerated curing for primarily logistical reasons.
3. Specify minimum SR of 24 kilohm-cm after 28-days of normal curing.
4. Continue accumulating results from different Class D and experimental PCC mixtures.

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CHAPTER 1 : INTRODUCTION

A key step for increasing bridge deck service life is to develop lower rapid chloride permeability (RCP) concrete mixtures. In this regard, TDOT Materials & Tests (M&T) Division is in the process of developing a new lower permeability bridge deck concrete specification, which calls for the evaluation of several alternative mixes. The current AASHTO procedure for determining chloride permeability of a concrete mix takes long and is expensive. Thus, for TDOT to reach decisions on alternative mixes being compared in a more timely way calls for a more rapid and accurate procedure for determining chloride permeability to be developed that would benefit both TDOT and its partners.

Benefits to TDOT

Delaying chlorides from reaching the critical reinforcement in bridge decks will extend bridge deck service life and reduce cost to TDOT. Less frequent need for maintenance / rehabilitation / reconstruction incursions into traffic will result in fewer traffic delays, increased safety, and greater efficiency through lower life cycle costs for Tennessee bridge decks. Having critical RCP information sooner would allow TDOT decision makers more latitude in achieving TDOT goals of safety, efficiency, and collaboration with local partners.

Purpose of the Proposed Research

Bridge deck mixture design development, mixture design submittals, quality control, and quality assurance testing could all be streamlined if concrete chloride permeability could be determined more rapidly; however, accuracy should not be sacrificed for speed. Fortunately, a

Virginia DOT researcher developed a curing regime that has shown promise in determining the results of rapid chloride permeability tests (RCPT) faster. In addition, a new surface resistivity (SR) method has gained favor with the Florida DOT. There has been some ambiguity, however, as to whether the accelerated curing correlates best with 56 or 91-day chloride permeability. The research will address this ambiguity as well as attempt to determine a rapid, efficient, and reliable means for determining concrete chloride permeability.

CHAPTER 2 : LITERATURE REVIEW

Bridge Deck PCC

According to a two-year study conducted by the National Association of Corrosion Engineers in 2001, 15% of the 583,000 bridges in the U.S. are structurally deficient because of corroded steel and steel reinforcement (1). As of December 2014, the total number of structurally deficient bridges in the U.S. was 61,365 and the number of functionally obsolete bridges was 84,525 (2). The number one cause of deterioration in reinforced concrete bridge decks is chloride-induced corrosion of reinforcing steel (3). The resistance of concrete to external forms of attack is reliant on its permeability (4). ACI defines permeability as "the ability of a given concrete to permit liquids or gases to pass through" (5). There are several factors that reduce the permeability of concrete. Some of the most important include: a low w/cm, incorporation of SCMs, the use of chemical admixtures such as high-range water reducers (HRWR), good workmanship for proper consolidation, and adequate moist curing (6).

Supplementary Cementitious Materials

The incorporation of SCMs such as fly ash or slag, is a more effective method of reducing concrete permeability than decreasing the w/cm (7; 8). This modification is especially important whenever high durability is a prescriptive requirement (9). Pozzolanic SCMs are beneficial to concrete because of their reaction with calcium hydroxide from portland cement hydration, producing additional calcium silicate hydrate. When properly substituted, SCMs decrease permeability and increase the ultimate strength (10; 11; 12). Ternary mixtures incorporate three cementitious materials: portland cement and two SCMs (13). Ternary mixtures provide even higher resistance to chloride ion penetrability and higher durability than plain PCC and binary mixtures (11, 14). Higher durability results in less cracking, spalling, loss of strength, and loss of mass (4). Thus, high durability is vital for extending the service life of concrete structures (15).

Slag

Ground granulated blast furnace slag (GGBFS) has been used as a SCM since 1774 (16). The production of GGBFS began in the United States in 1896 (16). Originally, GGBFS was used in the production of portland cement, but in the 1950s GGBFS began to be used as an SCM in concrete (16). GGBFS is a glassy, granular material formed from a rapid cooling process, usually by quenching the molten slag with water (17; 18). The molten slag originates as a byproduct of iron production (16). Iron oxide sources (ore, pellets, sinters) are melted using a blast-furnace that produces two products: molten iron and slag (16). After the rapid cooling process, the granular slag material is then ground in mills to a fineness that approximates that of portland cement (10). GGBFS is classified by its reactivity as either Grade 80, 100, or 120 (19). The compressive strength of mortar cubes consisting of equal portions of GGBFS and portland cement are compared to the compressive strength of portland cement mortar cubes to determine the reactivity of the GGBFS (19).

GGBFS is composed mainly of silica, alumina, calcium, and magnesium oxides (16). GGBFS is cementitious material that is referred to as a latent hydraulic material because of its slow hydration with water (20). When combined with portland cement, the hydration process of the portland cement accelerates the hydration of GGBFS (16). During the hydration of GGBFS with portland cement, GGBFS converts calcium hydroxide into additional calcium silicate hydrate similar to pozzolanic reactions (16). The variables that affect the cementitious properties of GGBFS in concrete are: the chemical composition, the alkali concentration in the mixture, the glass content of the GGBFS, the fineness of the GGBFS, and the temperature during the initial hydration phases (16).

The plastic properties effects of GGBFS as an SCM in PCC include: reduced water demand, improved workability, increased setting time, and altered bleeding rates (10). Some research has suggested that the reduction in water demand is due to GGBFS's lower absorption compared to portland cement (16). The workability and consolidation of PCC containing GGBFS has shown to increase due to a better particle dispersion and the higher fluidity of the paste (16). As the GGBFS percent replacement increases, the setting time of PCC increases due to the slow hydration rate of GGBFS (10; 16). The bleeding rate of PCC with GGBFS is affected based on the fineness of the GGBFS (16). As the fineness increases, the bleeding rate can be reduced and when a coarser GGBFS is used, the bleeding rate can increase (16). The bleeding rate of GGBFS PCCs can also increase due to the increased time of set and the non-absorptive qualities of dense GGBFS (16).

GGBFS hardened property effects include: lower early strength, higher or equal later strength, lower heat of hydration, higher alkali-aggregate reactivity resistance, decreased permeability, and higher durability (10). The strength gain rate is mainly dependent on the reactivity of the GGBFS and the percent replacement (16). As the percent replacement increases, the slope of the heat evolution curve becomes more gradual (10; 16). The peak heat of hydration temperature also decreases, reducing the chances of thermal cracking (10; 16). GGBFS also improves sulfate attack resistance and reduces alkali-aggregate reactivity with replacements exceeding 35% (10). The permeability of the concrete greatly reduces as the dosage of GGBFS increases (16). GGBFS PCCs provide better pore-size distribution and reduced pore connectivity when compared to ordinary PCCs (16). The reduced permeability then increases the concrete's resistance to deicing chemicals (16). The increased resistance to penetrating chloride ions from deicers further delay the risk of steel reinforcement corrosion (4; 16). Ternary PCC mixtures incorporating GGBFS provide greater durability and increased surface resistivity compared to ordinary PCC (21). These aspects make PCCs with GGBFS better qualified for structures required to face severe exposure conditions (15).

Class F fly ash

Fly ash is the most widely used SCM in concrete and has been used in the United States since the 1930s (10). Fly ash is a finely divided residue formed from the combustion of pulverized coal that is transported by flue gases and filtered by a particle removal system (17; 22). The main sources of fly ash generation are electric power-generating stations (10). The three different fly ashes (Class N, F, or C) are classified based on their pozzolanic or pozzolanic and cementitious properties as well as their chemical compositions (22). Class F fly ash is a pozzolanic fly ash produced from combustion of anthracite or bituminous coal (10; 22; 23). Class F fly ash is also referred to as "low calcium fly ash" because it usually contains less than 10 percent CaO (24). Class F fly ash is mainly composed of silica, alumina, and iron which are responsible for the ash's pozzolanic reactivity. Other components include calcium, magnesium, sulfur, potassium, and sodium (10). ASTM C618's chemical requirements for Class F fly ash consists of a 70% minimum sum of silicon dioxide (SiO2) + aluminum oxide (Al2O3) + iron oxide (Fe2O3) (22).

The quality of the fly ash depends on the loss of ignition (LOI), fineness, chemical composition, and uniformity (22; 24). LOI represents the amount of unburned carbon remaining in the fly ash. Higher LOI levels can lead to air entrainment complications in fresh concrete (24). ASTM C 618 limits the maximum LOI for Class F fly ash to 6% to reduce air entrainment absorption (10; 22). Air entrainment absorption results in a reduction in durability, especially for freeze-thaw resistance (18; 25).

Fineness is defined as the percent by weight of the material retained on the 45μm (No. 325) sieve (22). ASTM C 618 states the maximum fineness allowed is 34% for Class F fly ash (22). The achievable fly ash fineness is largely dependent on the condition of the coal crushers and the abrasive resistance of the parent coal (24). Coarser gradations tend to produce ash with less reactivity and higher carbon contents versus finer gradations (24). The uniformity of the ash simply refers to the consistency from shipment to shipment (24).

The spherical shape of fly ash particles produce a ball-bearing effect in the mixing process which provides a similar workability associated with an increased w/cm, thus reducing the required water demand (10; 24). When fly ash is substituted by weight, the lower specific gravity of fly ash causes an increase in paste volume, which further increases workability (10). Other fly ash substitution plastic property benefits include: reduced segregation, reduced bleeding, improved consolidation, and reduced heat evolution (10; 24).

The hardened property improvements of fly ash substitution stem from its pozzolanic nature which combines with calcium hydroxide, a byproduct of portland cement hydration, to produce additional calcium silicate hydrate allowing near complete utilization of portland cement and its byproducts (10; 24). The hardened concrete improvements of fly ash substitution include increased ultimate strength, decreased permeability, improved durability, improved sulfate attack resistance, and reduced alkali-aggregate reactivity (10). The reduction in permeability through fly ash replacements increases the chloride-ion penetration resistance, outperforming regular PCC durability wise (14).

Accelerated Curing

Concretes containing SCMs produce low early age strength and high early age permeability due to the slower pozzolanic reaction rate compared to ordinary portland cement (8). These concretes can then provide higher later age strength and lower permeability than regular PCC due to pozzolanic reactions, converting calcium hydroxide into additional calcium silicate hydrate (9). The different hydration rates have led to the recommendation of an extended moist curing period of 56 days for PCCs containing SCMs than the recommended 28 days of moist curing which is often used to classify ordinary PCC performance (15; 26).

A 28-day accelerated curing method for concretes containing SCMs has been recently proposed to provide an earlier potential property estimate than the previous 56-day moist curing recommendation (26). This curing method is suggested to be useful for slower hydrating SCMs, allowing for a reduction in test time and an increase in the overall production efficiency (9; 26; 27). The accelerated curing method consists of curing the specimens at 73.5 ° F for 7 days in accordance with ASTM C192, then immersing the specimens in another lime water curing tank at 100.5 ° F for the remaining 21 days as per ASTM C1202, section 8.2.3 (9; 26).

Research has shown that other 28-day elevated temperature moist curing methods produce equivalent room temperature properties ranging from 6 to 14 months (9; 27). The equivalent age is dependent upon the mixture’s proportions and the duration of elevated temperature curing (27). Some research has established correlations between the accelerated curing properties at earlier ages to the normally cured 56-day properties (28).

Accelerated curing methods are especially common at precast plants that utilize ordinary portland cement mixtures where initial property development is more important than the hindered long term performance. Higher initial strengths due to accelerated curing methods are associated with lower ultimate strengths (29). This also applies to durability; the high early age durability usually results in lower durability long term due to rapid initial hydration and the development of an unrefined pore structure (9). This effect on long term strength and durability has also been shown to apply to mixtures containing GGBFS or silica fume (7), although some research has shown that mixtures containing fly ash are not hindered by early elevated temperatures during curing, but rather that they exceed the long term potential of room temperature moist cured specimens (27).

Rapid Chloride Permeability Testing (ASTM C1202)

ASTM C1202, referred to as the Rapid Chloride Permeability Test (RCPT), is a test method that measures the concrete specimen's electrical conductance which is used to classify its resistance to penetrating chloride ions (26). The results from RCP testing could be obtained much more rapidly compared to the salt ponding test – after only 6 hours compared to 90 days (30; 31). This relatively high test speed allows for extensive testing of chloride permeability resistance. A direct voltage of 60V is applied through one side of the test cell that is filled with a 3% sodium chloride solution which saturates the side surface of the concrete specimen. The voltage then passes through the specimen and into the opposite side of the test cell which saturates the specimen in a 0.3 N sodium hydroxide solution (32; 33). A lower total charge passed through the specimen implies a lower permeability and a higher resistance to penetrating chloride ions (8). RCPT became a popular method of measuring the resistance of concrete to chloride ion penetration after its results were found to have good correlation with the 90-day salt ponding test (30; 31; 34).

The values obtained in the RCP test are often affected by several factors, including the movement of all ions present in the pore solution, as well as the aggregate type and any supplementary cementitious materials (SCMs) used (30; 31; 34). The addition of SCMs including fly ash and GGBFS lowers the chloride permeability of concrete by densifying the paste pore structure and reducing the pore structure's connectivity (8; 32). The additional incorporated SCM in ternary mixtures can lower the permeability of concrete even further, prolonging the time prior to reinforcement corrosion (21).

Additionally, RCP test results have been shown to result in high variability and are difficult to reproduce (34; 35). ASTM C 1202 allows up to a 42% variability between two specimens from the same batch (35). This high variability allows for a wide range of results that may not accurately depict the chloride permeability. The testing for RCP, therefore, requires a large number of samples in order to obtain a statistically valid estimate of the chloride permeability resistance of a mix. The validity of the RCPT has been questioned by several researchers for the temperature increase that occurs in the specimens (36). This has been suggested to increase the permeability, and this is now referred to as the Joule effect (36). Others doubt the test method because of the use of the sodium chloride solution which is thought to cause a reduction in the electrical charge passed, falsifying the results of lower permeability (3).

Surface Resistivity (AASHTO TP 95)

AASHTO TP 95 is a new test method used to identify the effects of different concrete additives on its electrical resistivity (37). Using concrete SR to estimate durability is gaining preference for the method's brisk and simple testing procedure as well as the emergence of the correlations between resistivity and permeability (38; 39). The results from SR testing can be obtained within minutes and are non-destructive in nature (40; 41). The FHWA has recently correlated the results from the SR test at 28 days with the results of the RCPT at 56 days as a means of determining concrete permeability (35). The study showed that SR provided the best combination of speed, ease of use, and repeatability (35; 42). The SR test not only proved to be an easier and faster test method but also provided a lower variability in test results compared to those yielded by RCPT (35).

The commonly used Wenner probe incorporates four equally spaced electrodes that apply a voltage between the outer probes while the inner probes measure the potential difference (42; 43). The handheld device then converts the measured electrical resistance into an apparent resistivity which has been correlated with the results of the RCPT (38; 42). Readings are taken around the cylinder specimen at 0°, 90°, 180°, and 270° twice, averaging the results for that specimen (44). A correction factor of 1.1 is then multiplied by the average of the readings to include the moist lime water curing condition (35). Higher readings indicate a higher resistance to chloride ion penetration.

The electrical resistance of concrete is dependent upon the microstructure of the paste and the moisture content (43). Concrete mixtures containing various SCMs have proven to significantly increase the SR by densifying the pore structure over time (45). Slower reacting SCMs including fly ash and GGBFS, at certain percent replacements, provide lower SR initially but can more than double the SR at ages greater than 91 days (42). Since not all SCMs develop at the same rate, the developing rate of SR also varies, meaning each variable should be finely tuned to achieve the highest SR possible (42). Class F fly ash has shown to increase the long-term SR due to its pozzolanic reaction and GGBFS has shown to increase the early-age SR (27). Thus, the use of both Class F fly ash and GGBFS in ternary mixtures provides higher SR overall, which corresponds to lower permeability and increased durability (10; 42). Surface resistivity testing has shown that the incorporation of ternary mixtures greatly contributes to increased electrical resistivity which can prolong the service life and while reducing the life-cycle cost of transportation pavements and structures (21).

Contrary to RCP, SR results may yield low variability and are easy to reproduce (35; 41). AASHTO TP 95 allows up to a 21% variability between two specimens from the same batch (37). This lower variability translates into not as wide a range in results and may provide a more accurate depiction of chloride permeability compared to that of RCP. The large number of samples tested are not as necessary to meet statistical requirements but rather as to resulting in an even lower variance in statistics computed from the collected data.

Rapid Chloride Permeability versus Surface Resistivity

Several research studies have been performed comparing RCP to SR to determine if a correlation exists between the results of the two test methods (30; 31; 35; 40; 41). Particularly, studies performed by the Federal Highway Administration (FHWA) (35), the Louisiana Transportation Research Center (LTRC) (46), the University of Tennessee (UT) (30), the University of Florida (UF) with the Florida Department of Transportation (FDOT) (31), and the University of Georgia (UGA) with the American Concrete Institute (ACI) (40) report a power function relationship between RCP and SR data with correlation coefficients larger than 0.85, which suggests that SR strongly correlates with RCP.

The trend reported in the FHWA study was based on data collected on a total of 25 mixtures that were obtained from a variety of mixture designs (35). Specifically, the mixtures used in this study consisted of differing water-to-cementing materials (w/cm) ratios, use of supplementary cementitious materials (SCMs), differing cementing materials contents, and differing coarse aggregate types; the mixtures were tested at 28 and 56 days (35). The FHWA study concluded that SR and RCP are highly correlated, with a correlation coefficient of 0.92 (35).

The trend reported by the LTRC study was based on data obtained from both laboratory and field specimens (46). The laboratory specimens consisted of five mixtures composed of differing w/cm ratio mixtures and differing SCMs that were tested at 14, 28, and 56 days (46). The field specimens were primarily from a Louisiana bridge project that were tested at 28 and 56 days (46). The LTRC study concluded that SR and RCP values correlate well, having a correlation coefficient of 0.89 (46).

The trend reported by the UT study was based on data obtained from bridge deck cores retrieved from bridge decks across Tennessee over three years; these specimens were tested at 28 and 56 days (30). The UT study concluded that a strong correlation was present between SR and RCP, with a correlation coefficient of 0.88 (30).

The trend reported by the UF study was also based on data obtained from field specimens; the specimens were obtained from various projects across Florida, which do include bridge deck mixtures (31). A total of 134 different mixtures, comprised of various SCMs, w/cm ratios, and coarse aggregate types which consisted of at least 500 sample sets, were used in the research; the specimens were tested at 28 and 91 days (31). The overall results for this research showed a strong correlation between SR and RCP at 28 and 91 days, with correlation coefficients of 0.94 and 0.93, respectively (31).

The trend reported by the UGA study was based on data of eight mixtures with varying w/cm ratios, SCMs, and cement composition (40). The mixtures were tested for SR at regular intervals until 56 days and tested for SR and RCP at 56 days (40). The UGA study observed that SR and RCP values show a strong correlation, with a correlation coefficient of 0.98.

While the above-mentioned studies were based on various aspects, including mixture designs, laboratory or field data, and testing day, the correlations from the studies followed trends similar to one another (30; 31; 35; 40; 46). The results from these studies provided a broader range of chloride permeability data, which can improve the correlation (30; 31; 35; 40; 46). Therefore, it would appear the SR results can be directly correlated to RCP results.

Density, Absorptions, and Voids Test (ASTM C642)

Class F fly ash and GGBFS in ternary PCC mixtures, at proper dosages and with proper moist curing, have proven to decrease the permeability and increase the durability of concrete (10; 47). The use of SCMs may decrease permeability but not always the porosity (48). The overall durability is increased through the reduction of the pore structure continuity (49).

ASTM C642 is a relatively simple test method that estimates concrete durability through determining the specimen's density, percent absorption, and percent voids in the hardened concrete (50). Lower permeability concretes better resist the penetration of moisture and other fluids which are vital for long-term durability (51). The oven drying portion of the test is likely to cause cracking which increases the specimen's percent absorption (33). Despite possible cracking and increased absorption, the test method is still useful for estimating long-term durability through determining the permeable percent voids in the hardened concrete (51).

CHAPTER 3 : MATERIALS

The coarse aggregate used in the research was a No. 57 stone from a local aggregate producer. The fine aggregate was river sand commonly used throughout middle Tennessee. Sieve analyses were conducted in triplicate on both coarse and fine aggregates as per AASHTO T 27 and AASHTO T 11 (52; 53). The average results of the sieve analysis on the aggregates are shown in Table 3.1. The analysis showed that the coarse aggregate met specifications for a No. 57 stone as per ASTM C 33 (54). The fine aggregate met the specifications for use in concrete as per TDOT 903.01 (57). Specific gravity and absorption testing were also conducted in triplicate on the coarse and fine aggregates as per AASHTO test methods T 85 and T 84, respectively (55; 56). The average results for the aggregates are shown in Table 3.2.

TABLE 3.1: Average Results from Sieve Analysis

Sieve Size (in)	Sieve Size (mm)	Coarse Aggregate Percent Passing	ASTM C33 (54) No. 57 Specification	Fine Aggregate Percent Passing	TDOT 903.01 (57) Fine Aggregate Specification
1.5	37.5	100	100	—	—
1	25	100	95-100	—	—
0.5	12.5	59	25-60	—	—
0.375	9.5	—	—	100	100
No. 4	4.75	3	0-10	98	95-100
No. 8	2.36	2	0-5	92	—
No. 16	1.18	—	—	83	50-90
No. 30	0.6	—	—	64	—
No. 50	0.3	—	—	8	5-30
No. 100	0.15	—	—	1	0-10
No. 200	0.075	—	—	0.4	0 - 3

TABLE 3.2: Average Results for Specific Gravity and Absorption

Property	Coarse Aggregate	Fine Aggregate
BSG (dry)	2.613	2.577
BSG (SSD)	2.651	2.609
Absorption (%)	1.42	1.25

Quantities of necessary aggregates were secured and stockpiled so that the same aggregates were used throughout the laboratory evaluation. Similarly, AASHTO M 295 (58) Class F fly ash (see Table 3.3), AASHTO M 302 (59) Grade 120 ground granulated blast furnace slag (GGBFS), and AASHTO M 194 (60) chemical admixtures were obtained from regional suppliers and stockpiled so that the same materials were used throughout the laboratory evaluation. Type I portland cement (PC) meeting AASHTO M 85 (55) criteria was obtained from a regional supplier. Local tap water was used for all laboratory mixtures.

TABLE 3.3: Class F Fly Ash Chemical Composition

Component	Percent Composition	ASTM C 618-12 (22) Requirements	AASHTO M 295-07 (58) Requirements
SiO_2	48.91	—	—
Al_2O_3	19.46	—	—
Fe_2O_3	16.41	—	—
$SiO_2 + Al_2O_3 + Fe_2O_3$	84.79	70% minimum	70% minimum
CaO	6.76	—	—
MgO	0.98	—	—
SO_3	1.91	5% maximum	5% maximum
Moisture Content	0.11	3% maximum	3% maximum
Na_2O	0.84	—	1.5% maximum
Loss-on-Ignition	1.37	6% maximum	5% maximum

CHAPTER 4 : PROCEDURE

Overview

The purpose of the project was to provide recommendations to TDOT on determining concrete chloride permeability rapidly and effectively. The research team reasoned that five initial questions needed to be answered. Specifically:

1. Is there good correlation between SR and RCP?
2. How well do RCP values measured at earlier ages correlate with RCP values measured at later ages?
3. How well do SR values measured at earlier ages correlate with SR values measured at later ages?
4. What are the advantages and disadvantages of accelerated curing of SR and RCP specimens?
5. Which test method (SR or RCP) is logistically superior?

The answers to these five initial questions allowed the research team to formulate well supported recommendations on the following topics:

A. Choice of test method (SR or RCP)
B. Choice of curing regime (normal or accelerated)

The strength of the answers to the initial questions and the subsequent recommendations are dependent on the amount of data collected in the study. Therefore, the research team attempted to maximize the amount and diversity of data on which the answers were based. The research team proceeded on the premise that data diversity would be limited to mixtures TDOT would consider using on a bridge deck (no water-to-cementing materials ratio (w/cm) > 0.40, no exotic materials, etc.). TDOT M&T management chose two mixtures for the project. Other data was obtained from current and past TTU projects to increase the amount of data available for correlations and predictions.

Mixtures Chosen by TDOT

TDOT M&T management chose two mixtures: a Class D with 20% Class F fly ash and a second mixture with 35% slag and 15% Class F fly ash. Each mixture was designed by trial batching. The trial batches were 1.35-ft^3 in size and were mixed in a 3.0-ft^3 nominal capacity rotary mixer in accordance with AASHTO R 39 (61). The mixture designs are shown in Table 4.1. The comparisons of each mixture with TDOT 604.03 are shown in Table 4.2.

TABLE 4.1: Mixture Designs

Component	TDOT Class D	50/35/15
Type I Portland Cement (lbs/CY)	496	310
Class F Fly Ash (lbs/CY)	124	93
Grade 120 Slag (lbs/CY)	0	217
No. 57 Limestone (lbs/CY SSD)	1857	1854
River Sand (lbs/CY SSD)	1118	1118
Water (lbs/CY)	229.5	229.5
Design Percent Air	7	7
Air Entrainer, oz/cwt (oz/CY)	0.5 (3.1)	1.55 (9.6)
ASTM C 494 Type A, oz/cwt (oz/CY)	0.1 (0.6)	1 (6.2)
ASTM C 494 Type F, oz/cwt (oz/CY)	3 (18.6)	2.1 (13.0)

TABLE 4.2: Comparison of Mixture Design Attributes with TDOT 604.03 Class D PCC Requirements

Quantity / Ratio / Percentage	TDOT 604.03 Class D PCC Requirement (62)	TDOT Class D	50/35/15
Cementing Materials Content (lbs/CY)	620 minimum	620	620
W/CM Ratio	0.40 maximum	0.370	0.370
Percent Fine Aggregate by Total Aggregate Volume	44 maximum	38	38
Percent Class F Fly Ash Substitution (by Weight) for PC	20 maximum for Class F	20	15
Percent Slag Substitution (by Weight) for PC	35 maximum	0	35

Validation Batches

Five validation batches of each mixture were produced and tested as per Table 4.3. Four 6x12-inch cylinders and three 3x6-inch cylinders were cast from each batch. After approximately 24 hours, the cylinders were de-molded and placed in lime-water kept at 73 ± 3° F as per AASHTO R 39 (61) until the specified testing time. Slump was determined in accordance with AASHTO T 119 (63). Unit weight and gravimetric air content were determined in accordance with AASHTO T 121 (64). Air content by pressure method was determined using a pressure meter in accordance with AASHTO T 152 (65). The temperature of concrete was determined in accordance with AASHTO T 30 (66). The 6x12-inch and 3x6-inch cylinders were cast and cured in accordance with AASHTO R 39 (61). The hardened concrete was tested for compressive strength in accordance with AASHTO T 22 (67) using un-bonded caps per ASTM C 1231 (68). Static modulus of elasticity was determined in accordance with ASTM C 469 (69). Absorption of hardened concrete after boiling was determined as per ASTM C 642 (50).

TABLE 4.3: Testing Protocol for Validation Batches

Number of Batches per Mixture	5
Size of each batch (ft^3)	1.35
Slump (AASHTO T 119)	1 per batch
Unit Weight and Gravimetric Air Content (AASHTO T 121)	1 per batch
Air Content by Pressure Method (AASHTO T 152)	1 per batch
Compressive Strength * @ 28 and 56 days (AASHTO T 22)	2 6x12 cylinders per date per batch
Static Modulus of Elasticity* @ 28 and 56 days (ASTM C 469)	1 of the 6x12 compressive strength cylinders per date per batch
Absorption and Voids in Hardened Concrete @ 56 days (ASTM C 642)	3 3x6 cylinders per batch

*- with neoprene pad caps in steel retainers

SR-RCP Batches of the TDOT Mixtures

Casting

Twenty SR-RCP batches of each mixture were produced and tested as per Table 4.4. Twenty-one 4x8-inch cylinders were cast from each batch. The 4x8-inch cylinders were cast in accordance with AASHTO R 39 (61).

Normally Cured Specimens

After approximately 24 hours, 15 of the 21 cylinders were de-molded and placed in lime-water tank at 73 ± 3° F as per AASHTO R 39 (61) until the specified testing time. The 4x8-inch cylinders were cured in accordance with AASHTO R 39 (61). Unfortunately, on the night of 6/11/14, the tank heaters went to maximum for several hours after an apparent power surge following a power outage. Approximately 30 cylinders were exposed to water temperatures up to 88.5°F until the following morning.

The hardened concrete was tested for RCP in accordance with AASHTO T 277 (70). The hardened concrete was tested for SR in accordance with AASHTO TP 95-11 (37). Following SR testing, the SR specimens were tested for compressive strength in accordance with AASHTO T 22 (67) using un-bonded caps per ASTM C 1231 (68).

Specimens Cured in an Accelerated Manner

After approximately 24 hours, six of the 21 cylinders were de-molded and placed in lime-water kept at 73 ± 3° F as per AASHTO R 39 until seven days after casting (61). Seven days after casting, the 4x8-inch cylinders were transferred to the 100 ± 3° F tank and cured in accordance

ASTM C 1202 with until the specified testing time (26). Testing for RCP, SR, and compressive strength were performed on the accelerated specimens in the same manner as normally cured specimens.

TABLE 4.4: Testing Protocol for RCP / Surface Resistivity Batches

Number of Batches per Mixture	20
Size of each batch (ft^3)	1.35
Rapid Chloride Permeability (AASHTO T 277)	3 samples cut from separate 4x8 cylinders per batch @ 28 days of accelerated curing 3 samples cut from separate 4x8 cylinders per batch @ 56 days of normal curing 3 samples cut from separate 4x8 cylinders per batch @ 91 days of normal curing
Surface Resistivity (AASHTO TP 95-11)	3 4x8 cylinders per batch @ 28 days of accelerated curing 3 4x8 cylinders per batch @ 28 days of normal curing 3 4x8 cylinders per batch @ 56 days of normal curing 3 4x8 cylinders per batch @ 91 days of normal curing
Compressive Strength * (AASHTO T 22)	Surface resistivity cylinders will be compression tested following surface resistivity testing

*- with neoprene pad caps in steel retainers

Other TTU RCP-SR Data Sets

The research team reasoned that both correlations and predictions would be stronger if based on larger and more diverse data sets. Therefore, the research team attempted to maximize the amount and diversity of data on which answers were based with the provision that data diversity would be limited to mixtures TDOT would consider using on a bridge deck (no w/cm > 0.40, no exotic materials, etc.). Four data sets containing both RCP and SR data on the same batches were available. A summary of the four data sets is provided in Table 4.5 and brief descriptions of each study are provided below.

TABLE 4.5: Other Available TTU RCP / Surface Resistivity Data

Mixture	Project	% C ash	% F ash	% Slag	28-day Accelerated Points	56-day Points	91-day Points
50/25/25F	TTU Slag Study	0	25	25	0	2	2
50/30/20F	TTU Slag Study	0	20	30	0	2	2
50/35/15F	TTU Slag Study	0	15	35	0	2	2
50/25/25C	TTU Slag Study	25	0	25	0	2	2
50/30/20C	TTU Slag Study	20	0	30	0	2	2
50/35/15C	TTU Slag Study	15	0	35	0	2	2
TDOT D 20F	TTU Aggregate Variable Study	0	20	0	0	16	0
TDOT D 100PC	TTU High Perm TDOT Class D	0	0	0	3	7	0
TDOT D 25C	TTU Aborted MS Thesis	25	0	0	0	8	10

TTU Slag Study

The unpublished TTU slag study was a preliminary attempt to determine if there was an optimum combination of slag and fly ash for 50% PC replacement. Early results revealed no discernable trend and the study was quickly abandoned.

TTU Aggregate Variable Study

The unpublished TTU aggregate variable study was a preliminary attempt to determine the effect of coarse and fine aggregate type on RCP and SR. Early results were promising and more testing is planned in the future.

TTU High Permeability Class D Mixture Study

NASCAR legend Richard Petty said, “You’ve got to have some slow guys to make the fast guys look fast.” This study was an attempt to provide some “slow guys.” Specifically, to determine how high RCP would rise (and how low SR would sink) if the worst available TDOT approved choices were made for the coarse aggregate and PC-supplementary cementing materials (SCM) matrix. It is important to note that the w/cm used met TDOT requirements. The designation of “worst available” referred to the poorest performing TDOT approved aggregates in the TTU Aggregate Variable Study. Additional testing is planned for a later time.

TTU Aborted MS Thesis Research

This study was an attempt to compare 10 batches of a TDOT Class D with a 25% Class C fly ash substitution to other TDOT Class D and Class D-lower permeability (LP) mixtures. However, the fast track BS-MS student decided to pursue other opportunities and the study was abandoned. Future plans include more tests and comparisons with a TDOT Class D mixture with 25% Class C fly ash substitution at a later time.

Other TTU SR Only Data Sets

The soon to be published “TTU Effect of Supplementary Cementing Materials on Surface Resistivity Study” was an attempt to determine the effect of different SCM combinations on SR development from one to 91 days. Three sets of three cylinders each, as required by AASHTO TP 95-11, were fabricated for each PC-SCM combination studied. A summary of the SCM combinations used in the study as well as the origin of the mixture designs is shown in Table 4.6. The 28, 56, and 91-day results were also used in the current project to enhance predictions of later date SR values with earlier date SR results.

TABLE 4.6: Other TTU Surface Resistivity Only Data

Mixture	Mixture Design from Project	% C ash	% F ash	% Slag	% SF	% MK	Sets
20F	Current	0	20	0	0	0	3
25F	SEFA 2013	0	25	0	0	0	3
25C	Aborted MS Thesis	25	0	0	0	0	3
3.5SF20F	TDOT D-LP	0	20	0	3.5	0	3
5SF25C	TDOT Catalog	25	0	0	5	0	3
3.5MK20F	TDOT D-LP	0	20	0	0	3.5	3
5MK25C	TDOT Catalog	25	0	0	0	5	3
45SL	TDOT D-LP	0	0	45	0	0	3
35SL15F	TDOT Catalog	0	15	35	0	0	3
100PC	New	0	0	0	0	0	3
45SL5MK	New	0	0	45	0	5	3
35SL15MK	New	0	0	35	0	15	3
50C	TDOT HVFA	50	0	0	0	0	3

CHAPTER 5 : RESULTS

Validation Batch Results

Plastic and hardened properties of the validation mixtures are shown in Tables 5.1, 5.2, 5.3, and 5.4, respectively. Complete results for 28 and 56-day compressive strengths, 28 and 56-day static modulus of elasticity, and 56-day hardened concrete absorption after boiling are shown in Appendices A, B, C, D, and E, respectively.

Validation Batch Data Quality

Plastic Properties

The acceptable range of plastic properties was determined by obtaining the single operator standard deviation from AASHTO R-39 Section 9 and multiplying by an ASTM C 670 factor for number of test results. All plastic property test results met the acceptable precision criteria.

Hardened Properties

The acceptable range was determined by first multiplying the test method multi-laboratory coefficient of variation (COV) by a factor from ASTM C 670 for the number of results. Finally, the product was multiplied by the mean result to obtain the allowable range. The multi-laboratory precision was used for 6x12 cylinders since AASHTO T 22 states that preparation of cylinders by different operators would probably increase the variation above multi-laboratory precision criteria. Single operator multi-batch precision was used for static modulus of elasticity since it was the only available precision criteria. All hardened property test results met the acceptable precision criteria.

TABLE 5.1: Plastic Property Results for TDOT Class D Validation Mixture

Batch #	Before HRWR Slump (inches)	After HRWR Slump (inches)	Pressure Method Air Content (%)	Gravimetric Air Content (%)	Unit weight (pcf)	Temperature (°F)
D - 1	2.50	7.75	7.1	6.8	141.9	76
D - 2	2.50	7.25	6.9	6.1	143.1	76
D - 3	2.50	7.75	6.8	6.1	143	77
D - 4	1.75	6.75	6.4	5.7	143.6	78
D - 5	2.00	7.25	6.9	6.1	143.1	77
Mean	2.25	7.35	6.82	6.16	142.91	76.80
Range	0.75	1.0	0.7	1.1	1.7	2.0
Acceptable Range	2.73	2.73	1.17	1.17	3.15	Not available
Meets?	Yes	Yes	Yes	Yes	Yes	—

TABLE 5.2: Plastic Property Results for the 50/35/15 Validation Mixture

Batch #	Before HRWR Slump (inches)	After HRWR Slump (inches)	Pressure Method Air Content (%)	Gravimetric Air Content (%)	Unit weight (pcf)	Temperature (°F)
S - 1	2.50	6	6.6	6.0	143.1	71
S - 2	2.50	7	7	6.8	141.8	71
S - 3	2.50	6.75	6.9	6.5	142.3	72
S - 4	2.50	6.75	6.6	6.0	143	72
S - 5	3.00	7	6.8	6.6	142.1	71
Mean	2.60	6.70	6.78	6.39	142.46	71.4
Range	0.5	1.0	0.4	0.86	1.3	1.0
Acceptable Range	2.73	2.73	1.17	1.17	3.15	Not available
Meets?	Yes	Yes	Yes	Yes	Yes	—

TABLE 5.3: Hardened Property Results for TDOT Class D Validation Mixture

Batch #	Mean 28-Day Compressive Strength (psi)	Mean 56-Day Compressive Strength (psi)	Mean 28-Day Static Modulus of Elasticity (psi)	Mean 56-Day Static Modulus of Elasticity (psi)	Mean 56-Day Absorption after Boiling (%)
D - 1	5160	5800	4350000	4300000	5.5
D - 2	4930	5730	4250000	4500000	5.4
D - 3	5080	5780	4400000	4400000	5.5
D - 4	5440	6020	4350000	4400000	5.2
D - 5	5380	6040	4300000	4350000	5.4
Mean	5198	5874	4330000	4390000	5.40
Range	510	310	150000	200000	0.3
Acceptable	Max range of 19.5% of mean = 1013	Max range of 19.5% of mean = 1145	Max range of 19.5% of mean = 844350	Max range of 19.5% of mean = 856050	Not available
Meets?	Yes	Yes	Yes	Yes	—

TABLE 5.4: Hardened Property Results for 50/35/15 Validation Mixture

Batch #	Mean 28-Day Compressive Strength (psi)	Mean 56-Day Compressive Strength (psi)	Mean 28-Day Static Modulus of Elasticity (psi)	Mean 56-Day Static Modulus of Elasticity (psi)	Mean 56-Day Absorption after Boiling (%)
S - 1	6370	7100	4600000	4550000	5.5
S - 2	6510	6970	4500000	4750000	5.3
S - 3	6280	7130	4400000	4700000	5.5
S - 4	6180	6730	4550000	5000000	5.6
S - 5	6020	6810	4550000	Damaged	5.3
Mean	6272	6948	4520000	4750000	5.44
Range	490	400	200000	450000	0.3
Acceptable	Max range of 19.5% of mean = 1223	Max range of 19.5% of mean = 1355	Max range of 19.5% of mean = 881400	Max range of 18.0% of mean = 855000*	Not available
Meets?	Yes	Yes	Yes	Yes	—

* - only 4 data points

SR-RCP Batch Results

Plastic properties were not conducted on the SR-RCP batches. Compressive strength, SR, and RCP results for the Class D and 50/35/15 SR-RCP batches are shown in Tables 5.5 through 5.10. Complete data for SR-RCP batch compressive strengths are shown in Appendices F through I. Similarly, complete SR-RCP SR data is shown in Appendices J through M. Complete SR-RCP RCP data is shown in Appendices N through P. Tables 5.11 and 5.12 show SR and RCP results for batches that had to be redone due to testing problems. Complete RCP data for the redone batches is shown in Appendix Q. Similarly, complete SR data for redone batches is shown in Appendix R.

SR-RCP Batch Data Quality

The acceptable range was determined by first multiplying the test method multi-laboratory COV by a factor from ASTM C 670 for number of results (the factor for 10 results was used since the table contained no higher values). Finally, the product was multiplied by the mean result to obtain the allowable range. The multi-laboratory precision was used since AASHTO T 22 states that preparation of cylinders by different operators would probably increase the variation above multi-laboratory precision criteria. All hardened property test results except 56-day compressive strength of TDOT Class D PCC met the acceptable range requirements. It is likely that the 56-day compressive strength of TDOT Class D PCC would have met the acceptable range if an ASTM C 670 factor for 20 test results was available or if AASHTO T 22 provided a multi-laboratory coefficient of variation for 4 x 8 cylinders.

TABLE 5.5: Compressive Strength Results for TDOT Class D Mixture SR-RCP Batches

Batch #	**28-Day Compressive Strength (psi)**	**28-Day Accelerated Compressive Strength (psi)**	**56-Day Compressive Strength (psi)**	**91-Day Compressive Strength (psi)**
D – 6	5490	6480	6140	7130
D – 7	5780	6990	6160	6800
D – 8	5270	6110	5850	6420
D – 9	5140	6100	5780	6470
D – 10	5530	6520	6190	6900
D – 11	5610	6480	6320	6930
D – 12	5270	6100	5820	6740
D – 13	5490	6410	6310	6830
D – 14	5450	6300	6100	6740
D – 15	5230	5740	5680	6350
D – 16	5790	6510	6230	6980
D – 17	6020	6860	6770	7100
D – 18	5390	6350	6230	6650
D – 19	5300	6060	6060	6610
D – 20	5910	6870	6910	7210
D – 21	5890	6890	6910	7340
D – 22	4960	5850	5520	6060
D – 23	5200	5710	5490	5980
D – 24	5490	6240	5970	6600
D – 25	4920	5630	5810	6120
Mean	5457	6310	6113	6698
Range	1100	1360	1420	1360
Acceptable	Max range of 22.5% of mean = 1228	Max range of 22.5% of mean = 1420	Max range of 22.5% of mean = 1375	Max range of 22.5% of mean = 1507
Meets?	Yes	Yes	No	Yes

TABLE 5.6: Compressive Strength Results for 50/35/15 Mixture SR-RCP Batches

Batch #	28-Day Compressive Strength (psi)	28-Day Accelerated Compressive Strength (psi)	56-Day Compressive Strength (psi)	91-Day Compressive Strength (psi)
S – 6	6270	7080	6740	7150
S – 7	6440	6950	6970	7040
S – 8	6750	7310	6780	7220
S – 9	6620	7270	6870	7450
S – 10	6560	7680	7850	7410
S – 11	6540	6860	7070	7390
S – 12	7410	7890	7280	8080
S – 13	7270	7820	7390	7810
S – 14	6950	7310	7280	7450
S – 15	7240	7570	7860	7800
S – 16	7470	7160	7460	7630
S – 17	6470	7410	6940	7120
S – 18	7060	7750	7560	7530
S – 19	6370	6840	7040	7230
S – 20	6920	7320	7160	7530
S – 21	7080	7600	7340	7760
S – 22	7300	7760	7520	7820
S – 23	7310	7760	7830	8120
S – 24	7110	7650	7300	7800
S – 25	6740	7800	7570	7760
Mean	6894	7440	7291	7555
Range	1200	1050	1120	1080
Acceptable	Max range of 22.5% of mean = 1551	Max range of 22.5% of mean = 1674	Max range of 22.5% of mean = 1640	Max range of 22.5% of mean = 1700
Meets?	Yes	Yes	Yes	Yes

TABLE 5.7: Surface Resistivity Results for TDOT Class D Mixture SR-RCP Batches

Batch #	28-Day Surface Resistivity (kilohm-cm)	28-Day Accelerated Surface Resistivity (kilohm-cm)	56-Day Surface Resistivity (kilohm-cm)	91-Day Surface Resistivity (kilohm-cm)
D – 6	14.7	26.9	18.7	27.7
D – 7	14.0	27.1	17.7	27.1
D – 8	14.4	25.6	20.3	25.7
D – 9	14.2	25.3	18.9	24.1
D – 10	13.6	24.9	18.6	26.7
D – 11	13.5	24.6	18.3	27.1
D – 12	14.4	24.9	19.4	27.7
D – 13	13.9	25.6	18.6	26.4
D – 14	13.6	25.9	19.6	24.9
D – 15	13.8	25.0	21.2	24.9
D – 16	13.3	25.2	18.8	24.6
D – 17	12.4	25.3	17.5	21.9
D – 18	13.8	24.0	19.8	24.9
D – 19	13.8	24.0	20.0	25.3
D – 20	13.7	22.4	18.3	24.8
D – 21	13.8	23.2	18.4	24.9
D – 22	13.3	21.5	19.7	25.5
D – 23	12.7	21.6	19.3	23.3
D – 24	14.3	23.4	16.5	27.3
D – 25	14.0	23.7	16.7	25.7
Mean	13.8	24.5	18.8	25.5
Range	2.3	5.6	4.7	5.8
Acceptable	Max range of 56.25% of mean = 7.7	Max range of 56.25% of mean = 13.7	Max range of 56.25% of mean = 10.5	Max range of 56.25% of mean = 14.3
Meets?	Yes	Yes	Yes	Yes

TABLE 5.8: Surface Resistivity Results for 50/35/15 Mixture SR-RCP Batches

Batch #	28-Day Surface Resistivity (kilohm-cm)	28-Day Accelerated Surface Resistivity (kilohm-cm)	56-Day Surface Resistivity (kilohm-cm)	91-Day Surface Resistivity (kilohm-cm)
S – 6	30.9	42.9	40.4	46.5
S – 7	31.4	44.1	40.8	45.4
S – 8	33.8	46.7	45.0	53.9
S – 9	32.6	44.6	44.0	51.0
S – 10	31.5	41.8	50.2	50.7
S – 11	31.8	42.4	48.7	50.5
S – 12	32.9	41.8	47.2	64.7
S – 13	29.4	41.3	43.9	61.1
S – 14	29.0	42.5	39.3	50.8
S – 15	29.6	41.7	39.2	48.0
S – 16	32.1	43.1	43.5	49.2
S – 17	29.9	44.0	39.6	46.2
S – 18	33.3	40.4	47.1	51.5
S – 19	32.0	42.9	44.5	51.6
S – 20	33.3	39.6	43.2	51.9
S – 21	32.3	39.0	42.4	50.6
S – 22	30.9	40.9	39.6	46.6
S – 23	30.3	39.3	38.1	45.7
S – 24	32.9	38.7	42.1	55.6
S – 25	31.4	39.8	41.3	56.5
Mean	31.6	41.9	43.0	51.4
Range	4.8	8.0	12.1	19.3
Acceptable	Max range of 56.25% of mean = 17.7	Max range of 56.25% of mean = 23.5	Max range of 56.25% of mean = 24.1	Max range of 56.25% of mean = 28.9
Meets?	Yes	Yes	Yes	Yes

TABLE 5.9: Rapid Chloride Permeability Results for TDOT Class D Mixture SR-RCP Batches

Batch #	28-Day Accelerated Rapid Chloride Permeability (Coulombs)	56-Day Rapid Chloride Permeability (Coulombs)	91-Day Rapid Chloride Permeability (Coulombs)
D – 6	1210	3100	1830
D – 7	1180	3140	1810
D – 8	1390	2940	1620
D – 9	1440	3010	1690
D – 10	1320	2700	1680
D – 11	1360	2760	1680
D – 12	1420	2620	1630
D – 13	1410	2640	1740
D – 14	1260	2780	1570
D – 15	1340	2670	1500
D – 16	1070	2790	1560
D – 17	1110	2870	1890
D – 18	1410	2650	1800
D – 19	1480	2690	1840
D – 20	1210	2780	1730
D – 21	1130	2760	1660
D – 22	1620	3170	2410
D – 23	1480	2720	2180
D – 24	1370	2800	1630
D – 25	1420	2700	1810
Mean	1332	2815	1763
Range	550	550	910
Acceptable	Max range of 81% of mean = 1078	Max range of 81% of mean = 2280	Max range of 81% of mean = 1428
Meets?	Yes	Yes	Yes

TABLE 5.10: Rapid Chloride Permeability Results for 50/35/15 Mixture SR-RCP Batches

Batch #	28-Day Accelerated Rapid Chloride Permeability (Coulombs)	56-Day Rapid Chloride Permeability (Coulombs)	91-Day Rapid Chloride Permeability (Coulombs)
S – 6	570	850	710
S – 7	570	810	690
S – 8	590	870	660
S – 9	600	910	670
S – 10	620	840	700
S – 11	610	850	720
S – 12	620	890	620
S – 13	660	830	540
S – 14	620	860	550
S – 15	640	850	470
S – 16	600	830	680
S – 17	620	900	650
S – 18	620	930	720
S – 19	630	930	650
S – 20	650	920	690
S – 21	700	980	630
S – 22	640	900	740
S – 23	640	950	650
S – 24	680	890	710
S – 25	660	900	670
Mean	627	885	656
Range	130	170	270
Acceptable	Max range of 81% of mean = 507	Max range of 81% of mean = 716	Max range of 81% of mean = 531
Meets?	Yes	Yes	Yes

TABLE 5.11: Surface Resistivity Results for SR-RCP Redo Batches

Batch #	28-Day Accelerated Surface Resistivity (kilohm-cm)	56-Day Surface Resistivity (kilohm-cm)	91-Day Surface Resistivity (kilohm-cm)
D – 22A	23.6	Problem	25.4
D – 23A	22.4	Problem	25.2
D – 22B	20.7	Problem	Discarded
D – 23B	20.0	Problem	Discarded
S – 12A	Problem	45.8	52.9
S – 13A	Problem	45.4	52.6
S – 14A	Problem	38.7	46.3
S – 15A	Problem	37.5	44.8

TABLE 5.12: Rapid Chloride Permeability Results for SR-RCP Redo Batches

Batch #	28-Day Accelerated Rapid Chloride Permeability (Coulombs)	56-Day Rapid Chloride Permeability (Coulombs)	91-Day Rapid Chloride Permeability (Coulombs)
D – 22A	1400	Problem	1760
D – 23A	1480	Problem	1780
D – 22B	1710	Problem	Discarded
D – 23B	1650	Problem	Discarded
S – 12A	Problem	840	730
S – 13A	Problem	850	740
S – 14A	Problem	860	700
S – 15A	Problem	840	710

Other SR and RCP Results

Other SR and RCP results for the unpublished TDOT Class D with 25% C, Slag-Fly Ash, and Aggregate Variable studies are shown in Tables 5.13 through 5.16. The entire data set for these studies are shown in Appendices S through Z.

Other SR and RCP Data Quality

The unpublished TTU TDOT Class D with 25% Class C fly ash contained enough batches of the same mixture to thoroughly evaluate the data quality. The other unpublished TTU studies contained too few batches of each mixture to evaluate data quality. As before, the acceptable range was determined by first multiplying the test method multi-laboratory COV by a factor from ASTM C 670 for the number of results. Finally, this product was multiplied by the mean result to obtain the allowable range. All SR and RCP results for the unpublished TTU TDOT Class D with 25% C met the acceptable range requirements.

TABLE 5.13: Surface Resistivity and Rapid Chloride Permeability Results from the Unpublished TTU Class D 25%C Study

Mixture / Batch #	56-Day Surface Resistivity (kilohm-cm)	91-Day Surface Resistivity (kilohm-cm)	56-Day Rapid Chloride Permeability (Coulombs)	91-Day Rapid Chloride Permeability (Coulombs)
TDOT D 25C - 1	21.3	28.6	2610	1700
TDOT D 25C – 2	20.3	25.3	3080	1940
TDOT D 25C – 3	20.9	27.3	2480	1790
TDOT D 25C – 4	20.7	27.5	2640	1720
TDOT D 25C – 5	20.8	28.8	2470	1990
TDOT D 25C – 6	18.7	25.5	2630	1950
TDOT D 25C – 7	No RCP for Pair	21.6	Power Outage	1780
TDOT D 25C – 8	No RCP for Pair	22.5	Power Outage	2010
TDOT D 25C - 9	22.2	25.0	2990	2150
TDOT D 25C - 10	21.7	25.2	2790	2160
Mean	20.8	25.7	2711	1919
Range	3.5	7.2	610	460
Acceptable	Max range of 53.75% of mean = 11.1	Max range of 56.25% of mean = 14.4	Max range of 77.4% of mean = 2098	Max range of 81% of mean = 1554
Meets?	Yes	Yes	Yes	Yes

TABLE 5.14: Surface Resistivity and Rapid Chloride Permeability Results from the Unpublished TTU Slag-Fly Ash Study

Mixture / Batch #	56-Day Surface Resistivity (kilohm-cm)	91-Day Surface Resistivity (kilohm-cm)	56-Day Rapid Chloride Permeability (Coulombs)	91-Day Rapid Chloride Permeability (Coulombs)
50/25/25F – 1	59.0	67.7	650	470
50/25/25F – 2	56.9	65.6	620	440
50/30/20F – 1	52.0	61.0	630	480
50/30/20F – 2	52.8	60.9	650	510
50/35/15F – 1	52.6	67.8	740	570
50/35/15F – 2	55.7	67.6	680	600
50/25/25C – 1	44.4	54.9	1050	800
50/25/25C – 2	43.5	53.7	1040	840
50/30/20C – 1	40.1	43.3	1060	950
50/30/20C – 2	39.7	43.3	1000	890
50/35/15C – 1	50.0	54.5	950	850
50/35/15C – 2	46.9	59.0	930	820

TABLE 5.15: Surface Resistivity and Rapid Chloride Permeability Results from the Unpublished TTU Aggregate Study

Mixture / Batch #	56-Day Surface Resistivity (kilohm-cm)	56-Day Rapid Chloride Permeability (Coulombs)
80/20 Sand Variable - 1	27.3	1840
80/20 Sand Variable - 2	25.9	2030
80/20 LSCA1 – 1	19.1	2470
80/20 LSCA1 - 2	20.8	2540
80/20 GRCA1 – 1	12.5	4870
80/20 GRCA1 - 2	11.0	5010
80/20 GRCA2 – 1	12.9	4430
80/20 GRCA2 - 2	11.9	3880
80/20 LSCA2 – 1	18.7	2300
80/20 LSCA2 - 2	18.5	2810
80/20 LSCA3 – 1	23.2	2220
80/20 LSCA3 - 2	22.0	2470
80/20 LSCA4 – 1	20.7	2450
80/20 LSCA4 - 2	20.3	2620
80/20 LSCA5 – 1	19.8	2340
80/20 LSCA5 - 2	20.8	2580
100PC GRCA1 – 1	12.7	4150
100PC GRCA1 - 2	11.1	4130
100PC GRCA1 - 3	11.1	4240
100PC GRCA2 - 1	9.4	4650
100PC GRCA2 - 2	10.0	4950
100PC GRCA2 - 3	10.8	4520
100PC GRCA2 - 4	10.0	5150

TABLE 5.16: Accelerated Surface Resistivity and Rapid Chloride Permeability Results from the Unpublished TTU Aggregate Study

Mixture / Batch #	28-Day Accelerated Surface Resistivity (kilohm-cm)	28-Day Accelerated Rapid Chloride Permeability (Coulombs)
100PC GRCA1 – 1	9.3	4110
100PC GRCA1 - 2	9.9	3870
100PC GRCA1 - 3	9.6	4140

Other SR Only Results

Available SR results for the as of yet unpublished “TTU Effect of Supplementary Cementing Materials on Surface Resistivity Study” are shown in Tables 5.17 through 5.19. The complete data for these studies are shown in Appendices AA through AC.

Other SR Only Data Quality

The as of yet unpublished “TTU Effect of Supplementary Cementing Materials on Surface Resistivity Study” contained only three batches of each mixture. The authors felt this was sufficient to evaluate the data’s quality. As before, the acceptable range was determined by first multiplying the test method multi-laboratory COV by a factor from ASTM C 670 for number of results. Finally, the product was multiplied by the mean result to obtain the allowable range. All SR results for as of yet unpublished “TTU Effect of Supplementary Cementing Materials on Surface Resistivity Study” met the acceptable range requirements.

TABLE 5.17: 28-day Surface Resistivity Results for the Unpublished Effect of SCM on SR Study

Mixture	Batch 1 Result (kilohm-cm)	Batch 2 Result (kilohm-cm)	Batch 3 Result (kilohm-cm)	Mean Result (kilohm-cm)	Acceptable Range = 0.4125 * Mean (kilohm-cm)	Meets?
20F	12.4	13.0	13.2	12.9	5.3	Yes
25F	14.1	14.3	14.0	14.1	5.8	Yes
25C	12.5	12.8	12.7	12.7	5.2	Yes
3.5SF20F	27.5	28.1	28.4	28.0	11.5	Yes
5SF25C	31.1	30.3	29.3	30.2	12.4	Yes
3.5MK20F	30.9	29.7	29.3	30.0	12.3	Yes
5MK25C	33.1	33.1	32.8	33.0	13.6	Yes
45SL	29.9	30.9	32.7	31.2	12.8	Yes
35SL15F	31.8	31.8	30.6	31.4	12.9	Yes
100PC	12.3	11.5	12.0	11.9	4.9	Yes
45SL5MK	101.4	100.5	101.1	101.0	41.6	Yes
35SL15MK	139.7	137.9	139.7	139.1	57.3	Yes
50C	13.1	13.0	12.6	12.9	5.3	Yes

TABLE 5.18: 56-day Surface Resistivity Results for the Unpublished Effect of SCM on SR Study

Mixture	Batch 1 Result (kilohm-cm)	Batch 2 Result (kilohm-cm)	Batch 3 Result (kilohm-cm)	Mean Result (kilohm-cm)	Acceptable Range = 0.4125 * Mean (kilohm-cm)	Meets?
20F	17.7	18.1	17.9	17.9	7.3	Yes
25F	22.1	22.5	22.1	22.2	9.1	Yes
25C	17.8	18.2	18.0	18.0	7.4	Yes
3.5SF20F	43.3	44.8	45.0	44.4	18.3	Yes
5SF25C	53.2	50.3	49.1	50.9	20.9	Yes
3.5MK20F	40.1	37.7	37.3	38.4	15.8	Yes
5MK25C	41.5	41.0	40.6	41.0	16.9	Yes
45SL	35.9	36.9	38.0	36.9	15.2	Yes
35SL15F	45.2	45.1	44.1	44.8	18.4	Yes
100PC	14.6	13.3	14.0	14.0	5.7	Yes
45SL5MK	114.2	114.2	115.8	114.7	47.3	Yes
35SL15MK	172.2	172.7	177.6	174.2	71.8	Yes
50C	22.6	21.8	21.4	21.9	9.0	Yes

TABLE 5.19: 91-day Surface Resistivity Results for the Unpublished Effect of SCM on SR Study

Mixture	Batch 1 Result (kilohm-cm)	Batch 2 Result (kilohm-cm)	Batch 3 Result (kilohm-cm)	Mean Result (kilohm-cm)	Acceptable Range = 0.4125 * Mean (kilohm-cm)	Meets?
20F	29.2	29.3	28.5	29.0	11.9	Yes
25F	36.0	34.9	34.9	35.3	14.5	Yes
25C	27.9	28.3	28.0	28.1	11.5	Yes
3.5SF20F	58.1	59.3	59.7	59.0	24.3	Yes
5SF25C	70.5	66.1	64.4	67.0	27.6	Yes
3.5MK20F	51.0	49.1	47.2	49.1	20.2	Yes
5MK25C	50.7	49.1	48.6	49.5	20.4	Yes
45SL	44.1	45.3	47.9	45.8	18.8	Yes
35SL15F	55.0	55.0	53.3	54.4	22.4	Yes
100PC	17.8	16.3	16.7	16.9	6.9	Yes
45SL5MK	127.8	124.4	125.5	125.9	51.9	Yes
35SL15MK	196.8	197.3	205.3	199.8	82.4	Yes
50C	34.3	31.5	31.6	32.5	13.4	Yes

Previous TDOT RCP Results

RCP results from previous TDOT projects are shown in Table 5.20. The complete RCP data set for these studies are shown in Appendices AD through AG.

TABLE 5.20: Comparison RCP Values from Previous TDOT Projects

Project	Mixture	Batches x Specimens	Mean Value	COV (%)	Range (Coulombs)	Meets COV or Range Requirements?
RES 2010-007	Class D 20% F	50 x 2	1536	11.0	NA	Yes COV
RES 2010-035	Class D 20% F	10 x 2	1220	4.9	200	Yes Both
RES 2011-09	45% SL	10 x 3	813	8.0	200	Yes Both
RES 2011-09	20% F 3.5% SF	10 x 3	788	6.2	150	Yes Both
RES 2011-09	20% F 3.5% MK	10 x 3	744	7.5	190	Yes Both
RES 2013-11	25% C 5% SF	11 x 3	521	14.0	220	Yes Range
RES 2013-11	25% C 5% MK	11 x 3	766	3.2	70	Yes Both
RES 2013-11	35% SL 15% F	11 x 3	780	5.7	150	Yes Both
RES 2013-11	35% F 3% MK	11 x 3	899	6.0	150	Yes Both

CHAPTER 6 : ANALYSIS OF RESULTS

TDOT Specification Compliance

All validation batch plastic properties (see Tables 5.1 and 5.2) met TDOT Class D PCC requirements. Similarly, all validation batch compressive strengths (see Tables 5.3 and 5.4) met TDOT Class D PCC requirements. Finally, all SR-RCP batch compressive strengths (see Tables 5.5 and 5.6) met TDOT Class D PCC requirements.

Comparison with Previous TDOT Project RCP Results

The current TDOT Class D results at 56 days (Table 5.9) were compared with the Class D 56-day results from RES 2010-007 since the mixture designs for these mixtures were very similar. Similarly, the current TDOT Class D results at 91 days (Table 5.9) were compared with the Class D 91-day results from RES 2010-035. The current 56-day 50/35/15 results (Table 5.10) were compared with the 56-day results of the 50/35/15 mixture from RES 2013-11 since the mixture designs were very similar. The current 56-day 50/35/15 results (Table 5.10) were also compared with the 56-day results of the 45% slag mixture from RES 2011-09. Current results were not statistically compared with the mixtures containing silica fume or metakaolin from Table 5.20. The results from all the above comparisons is presented in Table 6.1.

TABLE 6.1: Statistical Comparisons with Results from Previous TDOT Projects

Concrete Mixes Compared	|T statistic|	Interpretation of Test Result
Current TDOT Class D at 56 days (Table 5.9) compared to TDOT Class D at 56 days from RES 2010-007	28.50	Mean RCP for current TDOT Class D mix at 56 days is significantly higher than the mean RCP of mix in RES 2010-007 at 56 days
Current TDOT Class D at 91 days (Table 5.9) compared to TDOT Class D at 91 days from RES 2010-035	10.60	Mean RCP for current TDOT Class D mix at 91 days is significantly higher than the mean RCP of mix in RES 2010-035 at 91 days
Current 50/35/15 at 56 days (Table 5.10) compared to 50/35/15 at 56 days from RES 2013-11	15.06	Mean RCP for current 50/35/15 mix at 56 days is significantly higher than the mean RCP of 50/35/15 mix in RES 2013-11 at 56 days
Current 50/35/15 at 56 days (Table 5.10) compared to 45% slag mixture at 56 days from RES 2011-09	3.12	Mean RCP for current 50/35/15 mix at 56 days is significantly higher than the mean RCP of the 45% slag mix in RES 2011-09 at 56 days

SR-RCP Correlations

Figures 6.1 through 6.3 show SR-RCP correlations for all available results, for normally cured results, and for results of samples moist cured in an accelerated manner, respectively. For comparison, the results based on some equations found in the literature are provided on each plot. Tables 6.2 through 6.4 display SR-RCP statistical analysis for all available results, for normally cured results, and for results from samples moist cured in an accelerated manner, respectively. A discussion of these results is provided below.

Statistical Analysis of SR-RCP Correlations

TTU RCP Data and AASHTO RCP Equation

To judge how well the AASHTO equation represents the data generation process for the TTU Data, the RCP values of the TTU Data were regressed on corresponding RCP data values generated by the AASHTO equation with SR values as input. If the AASHTO equation predicts RCP values that are identical to the observed TTU RCP Data, then the simple linear model will have an intercept with a value of 0 and a slope of value 1. Significant deviations from these two parameter values would be indicative of the AASHTO equation giving RCP predictions that differ from the observed TTU RCP data. The least squares regression line obtained was TTU RCP = 46.776 + 1.016 AASHTO RCP ($R^2 = 0.89$). The t-statistic for the test of the null hypothesis of the estimated intercept being 0 was 0.99 while that for the test of the slope being 1 was 0.62. Based on these results, the intercept is not significantly different from 0 while the slope is not significantly different from 1. The intercept term was thus constrained to a value of 0, which yielded an equation TTU RCP = 1.037 AASHTO RCP ($R^2 = 0.96$). The t-test was then used to test the null hypothesis of the slope parameter being equal to 1. Using a five percent level of significance, the estimated coefficient of the AASHTO RCP values was significantly different from 1 (see Table 6.2), indicating that the AASHTO equation does not perfectly represent the data generation process responsible for generating the TTU data. On average, the TTU RCP data were 3.7% greater than those given by the AASHTO equation.

More directly, the estimated parameters of the TTU RCP Data model (shown in Figure 6.1) were compared to the parameters of the AASHTO RCP equation (also shown in Figure 6.1) to determine whether or not corresponding model parameters were statistically equal. Note that each equation is a power function of the form cx^p where c is a coefficient, p is the power, and x is the variable. T-tests were performed on the parameters, that is, c and p. For the tests, the AASHTO model parameters were treated as non-random. The hypothesis of equality of corresponding model parameters was rejected at the five percent level of significance (the t-statistic for the equality of the coefficient c in both equations was 2.175 while that for the power p was 2.092).

TTU RCP Data and FHWA Tech Brief Equation

To judge how well the FHWA Tech Brief equation represents the data generation process for the TTU Data, the RCP values of the TTU Data were regressed on corresponding RCP data values generated by the FHWA Tech Brief equation with SR values as input and this yielded the equation TTU RCP = 251.044 + 1.109 FHWA RCP ($R^2 = 0.87$). The t-statistic for the test of the null hypothesis of the estimated intercept being 0 was 5.50 while that for the test of the slope being 1 was 3.68. Based on these results, the intercept is significantly different from 0 and the slope is significantly different from 1. With the intercept term exceeding 0 and the slope also exceeding 1, it is indicative of the TTU RCP values on average being higher than the corresponding RCP values given by the FHWA Tech Brief equation.

Given that the intercept is significantly different from 0, by what percentage the observed TTU RCP data are on average larger or smaller than those yielded by the FHWA Tech Brief equation is determined as follows:

The general linear relationship between the observed TTU RCP data and the predicted values is given by the equation:

$$\text{TTU RCP} = \alpha_0 + \alpha_1\text{FHWA RCP} \qquad (1)$$

Were the predicted RCP values to be identical to the observed RCP values then the estimated value of α_0 would not be significantly different from 0 while the estimated value of α_1 would not be significantly different from 1. This was not the case above. Therefore, the difference between corresponding RCP values is:

$$\text{TTU RCP - FHWA RCP} = \alpha_0 + \alpha_1\text{FHWA RCP - FHWA RCP} \qquad (2)$$

Expressing the difference in values as a percentage yields:

$$\left(\frac{(\text{TTURCP - FHWA RCP})\times 100}{\text{TTURCP}}\right) = \left(\frac{[\alpha_0 + (\alpha_1 - 1)\text{FHWA RCP}\times 100}{\text{TTURCP}}\right) \quad (3)$$

Since the mean difference between the two sets of values expressed as a percentage is sought, the expected value of Equation (3) is taken yielding:

$$E\left(\frac{(\text{TTURCP - FHWA RCP})\times 100}{\text{TTURCP}}\right)=E\left(\frac{[\alpha_0+(\alpha_1-1)\text{FHWA RCP}\times 100}{\text{TTURCP}}\right) \qquad (4)$$

Applying Equation (4) showed that the RCP predictions given by the FHWA Tech Brief equation were on average 24% lower than the observed TTU RCP data.

More directly, the estimated parameters of the TTU Data model (shown in Figure 6.1) were compared to the parameters of the FHWA Tech Brief equation (shown in Figure 6.1) to determine whether or not corresponding model parameters were statistically equal. Note that each equation is a power function (cx^p where c is a coefficient, p is the power, and x is the variable). T-tests were performed on the parameters c and p. For the tests, the FHWA Tech Brief model parameters were treated as non-random. The hypothesis of equality of the power parameter p was rejected at the five percent level of significance (t-statistic was 2.572). However, that of the coefficient c was not rejected (t-statistic was 0.109). Rejection of the null hypothesis of equality of at least one of the model parameters is indicative of the two equations not being statistically identical.

TTU Data and LRTC Equation

To judge how well the LRTC equation represents the data generation process for the TTU Data, the RCP values of the TTU Data were regressed on corresponding RCP data values generated by the LRTC equation with SR values as input and this yielded the equation TTU RCP = -474.637 + 1.582 LTRC RCP ($R^2 = 0.90$). The t-statistic for the test of the null hypothesis of the estimated intercept being 0 was -8.65 while that for the test of the hypothesis of the slope being 1 was 15.65. Based on these results, the intercept is significantly different from 0 and the slope is significantly different from 1.

After making the appropriate changes to Equation (4) and applying it to this context showed that the RCP predictions given by the LTRC equation were on average 18% lower than the observed TTU RCP data.

More directly, the estimated parameters of the TTU Data model (shown in Figure 6.1) were compared to the parameters of the LRTC equation (shown in Figure 6.1) to determine whether or not corresponding model parameters were statistically equal. Again, note that each equation is a power function of the form cx^p where c is a coefficient, p is the power, and x is the variable. The t-test was used, and for it, the LRTC model parameters were treated as non-random. The hypothesis of equality of corresponding model parameters was rejected at the five percent level of significance for both parameters c and p (t-statistic for the test of equality of the coefficient was 11.425 while that for the test of the equality of the power was 10.577) indicating that the two equations are not statistically identical.

AASHTO Equation and FHWA Tech Brief Equation

To determine the degree of similarity between the RCP values given by the AASHTO equation and the RCP values given by the FHWA Tech Brief equation, SR values were input into both equations to yield corresponding values of RCP. The RCP values given by the AASHTO equation were then regressed on the RCP values given by the FHWA Tech Brief equation. This yielded the equation AASHTO RCP = 192.955 + 1.095 FHWA RCP ($R^2 = 0.998$). The t-statistic for the test of the null hypothesis of the estimated intercept being 0 was 38.829 while that for the test of the hypothesis of the slope being 1 was 30.448. Based on these results, the intercept is significantly different from 0 and the slope is significantly different from 1. With the intercept term far exceeding 0 and the slope also exceeding 1, it is indicative of the RCP values given by the AASHTO equation on average being greater than the corresponding RCP values given by the FHWA Tech Brief equation.

After making the appropriate changes to Equation (4) and applying it to this context showed that the RCP predictions given by the FHWA Tech Brief equation were on average 20% lower than the RCP predictions given by the AASHTO equation.

AASHTO Equation and LRTC Equation

To determine the degree of similarity between the RCP values given by the AASHTO equation and by the LRTC equation, SR values were input into both equations to yield corresponding values of RCP. A linear regression analysis was performed between the RCP values given by the AASHTO equation and the RCP values given by the LRTC equation, which yielded the equation: AASHTO RCP = -491.674 + 1.541 LTRC RCP (R^2 = 0.994). The t-statistic for the test of the null hypothesis of the estimated intercept being 0 was -39.412 while that for the test of the null hypothesis of the slope being 1 was 63.999. Based on these t-test results, the intercept is significantly different from 0 and the slope is significantly different from 1.

After making the appropriate changes to Equation (4) and applying it to this context showed that the RCP predictions given by the LRTC equation were on average about 15% lower than the RCP predictions given by the AASHTO equation.

LRTC Equation and FHWA Tech Brief Equation

To determine the degree of similarity between the RCP values given by the LRTC equation and the FHWA Tech Brief equation, SR values were input into both equations to yield corresponding values of RCP. A linear regression analysis was performed between the RCP values given by the LRTC equation and the RCP values given by the FHWA Tech Brief equation, which yielded the equation: LRTC RCP = 452.456 + 0.706 FHWA RCP (R^2 = 0.986). The t-statistic for the test of the null hypothesis of the estimated intercept being 0 was 49.287 while that for the test of the null hypothesis of the slope being 1 was -49.194. Based on these t-test results, the intercept is significantly different from 0 and the slope is significantly different from 1. These results indicate the two equations do not yields statistically similar predictions of RCP.

An inspection of Figure 6.1 shows that there is a range of SR values for which the LTRC equation gives RCP predictions that are lower in magnitude than the corresponding predictions given by the FHWA Tech Brief equation and vice versa. Applying the appropriately modified version of Equation (4) showed that the FHWA Tech Brief predictions are on average about 17% higher than the predictions given by the LTRC equation for SR values not exceeding 19.1 kilohm-cm. For SR values exceeding 19.1 kilohm-cm, the results showed the RCP predictions by the FHWA Tech Brief equation were on average about 16% lower than the predictions given by the LRTC equation.

TTU 56-Day and 91-Day Equation and AASHTO Equation

The null hypothesis of the equality of corresponding parameters of the TTU 56-day and 91-day RCP equation and the AASHTO RCP equation (both equations are presented in Figure 6.2) was tested using a statistical t-test. The absolute t-value obtained for the test of the equality of the power parameter was 3.51 while that for the equality of the coefficient was 4.71. Based on these t-statistics and a five percent level of significance, significant differences were found to exist between corresponding parameter estimates.

When the TTU 56-day and 91-day RCP data were regressed on predictions given by the AASHTO RCP equation, the following equation was obtained: TTU 56-day and 91-day RCP = 60.192 + 1.092 AASHTO RCP ($R^2 = 0.940$). The t-statistic for the test of the null hypothesis of the estimated intercept being 0 was 1.469 while that for the test of the null hypothesis of the estimated slope being 1 was 4.122. Based on these t-test results, the null hypothesis of the estimated intercept being 0 is not rejected, however, the estimated slope significantly exceeds 1 indicating that TTU 56-day and 91-day RCP values are on average higher than the corresponding RCP values predicted by the AASHTO equation.

Applying the appropriately modified version of Equation (4) showed that the RCP predictions given by the AASHTO equation were on average about 12% lower those given by the TTU 56-day and 91-day equation.

Further, when the TTU 56-day and 91-day RCP data were regressed on predictions given by the AASHTO RCP equation with the intercept term constrained to a value of 0, the following equation was obtained: TTU 56-day and 91-day RCP = 1.119 AASHTO RCP ($R^2 = 0.982$). Were the RCP values predicted by the AASHTO equation to be similar to the TTU 56-day and 91-day RCP values, the estimated slope would be statistically equal to 1. A statistical test of the null hypothesis of the slope being 1 gave a t-value of 9.792, resulting in a rejection of the null hypothesis. Based on the equation, the TTU 56-day and 91-day RCP values were on average about 11.9% higher than the values given by the AASHTO equation (Table 6.3).

TTU 28-Day Equation and AASHTO Equation

The hypothesis of equality of the parameters of the TTU 28-day RCP equation and the AASHTO RCP equation were directly tested (equations are shown in Figure 6.3) using a statistical t-test. Each equation is a power function of the form cx^p where c is a coefficient, p is the power, and x is the variable.

The t-statistic for the test of the null hypothesis of equality of the coefficient c in both equations was 0.34. Using a five percent level criterion, t-critical was determined to be 2.01. Hence, the null hypothesis of equality of the coefficient in the two equations could not be rejected.

The t-value for the null hypothesis of equality of the power *p* in both equations was 3.14, indicating a significant difference between the powers in the two equations. With the estimated power-parameters of the two equations being significantly different from each other, it points to the two equations yielding significantly different predictions of RCP for the same input of SR.

When the TTU 28-day RCP data were regressed on the predictions given by the AASHTO RCP equation, the following equation was obtained: TTU 28-day RCP = -37.732 + 0.797 AASHTO RCP ($R^2 = 0.986$). The t-statistic for the test of the null hypothesis of the estimated intercept being 0 was -1.428 while that for the test of the null hypothesis of the estimated slope being 1 was 14.524. Based on these t-test results, the null hypothesis of the estimated intercept being 0 is not rejected. However, the estimated slope is significantly less than 1 indicating that the TTU 28-day RCP values are on average lower than the values predicted by the AASHTO RCP equation.

Applying the appropriately modified version of Equation (4) showed that the RCP predictions given by the AASHTO equation were on average about 29% higher in magnitude than the RCP predictions given by the TTU 28-day equation (reported in Table 6.4).

TTU 28-Day Equation and FHWA Tech Brief Equation

The hypothesis of equality of the parameters of the TTU 28-day equation and the FHWA Tech Brief equation were directly tested (equations are shown in Figure 6.3) using statistical t-tests. Again, both equations are power functions defined generally as cx^p, where *c* is the coefficient, *p* is the power, and *x* is the variable. The absolute t-value for the test of the null hypothesis of equality of the coefficient *c* was 1.86. Using a five percent level criterion, the null hypothesis of equality of the coefficient in the two equations cannot be rejected (t-critical is 2.01). The t-value for the null hypothesis of equality of the power *p* in both equations was 1.74. Given t-critical is 2.01, again, the null hypothesis of equality of the power in both equations cannot be rejected.

When the TTU 28-day RCP data were regressed on the predictions given by the FHWA Tech Brief RCP equation, the following equation was obtained: TTU 28-day RCP = 143.759 + 0.856 Tech Brief RCP ($R^2 = 0.982$). The absolute t-value for the test of the null hypothesis of the estimated intercept being 0 was 5.294 while that for the test of the null hypothesis of the estimated slope being 1 was 8.426 (reported in Table 6.4). Based on these t-test results, the null hypothesis of the estimated intercept being 0 is rejected. Additionally, the null hypothesis of the estimated slope being equal to 1 is also rejected. These results point to significant differences between corresponding values of TTU 28-day RCP and RCP predictions given by the FHWA Tech Brief equation.

Applying the appropriately modified version of Equation (4) showed that the RCP predictions given by the FHWA Tech Brief equation were on average about 3% higher in magnitude than the RCP predictions given by the TTU 28-day equation

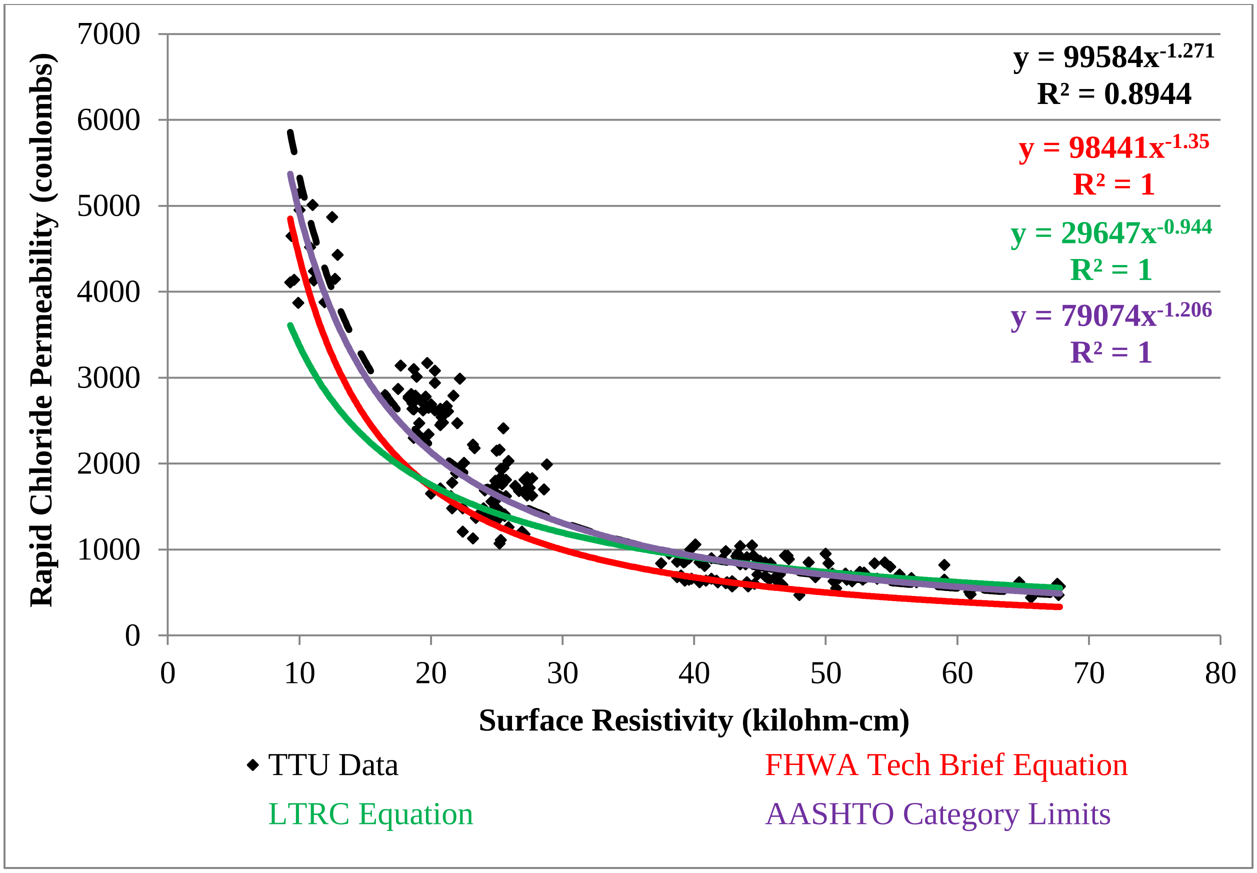

FIGURE 6.1: SR-RCP Correlation with All Available TTU Data

TABLE 6.2: Statistical Comparisons of Data and Equations in Figure 6.1

Data Sets to be Compared	**|T Statistic| Slope = 1**	**Statistical Difference?**	**How much Higher/Lower on Average?**
TTU Data and AASHTO Equation	2.649	Yes	TTU data on average about 4% higher than predicted by AASHTO equation
TTU Data and FHWA Tech Brief Equation	3.68	Yes	FHWA Tech Brief predictions on average about 24% lower than TTU data
TTU Data and LTRC Equation	15.650	Yes	LTRC equation predictions on average 18% lower than TTU data
AASHTO Equation and FHWA Tech Brief Equation	30.448	Yes	FHWA TB predictions on average 20% lower than AASHTO predictions
AASHTO Equation and LTRC Equation	63.999	Yes	LRTC equation predictions on average about 15% lower than AASHTO predictions
LTRC Equation and FHWA TB Equation	49.194	Yes	For SR ≤ 19: FHWA TB predictions on average 17% higher than LTRC predictions. For SR > 19: FHWA TB predictions on average 16% lower than LTRC predictions.

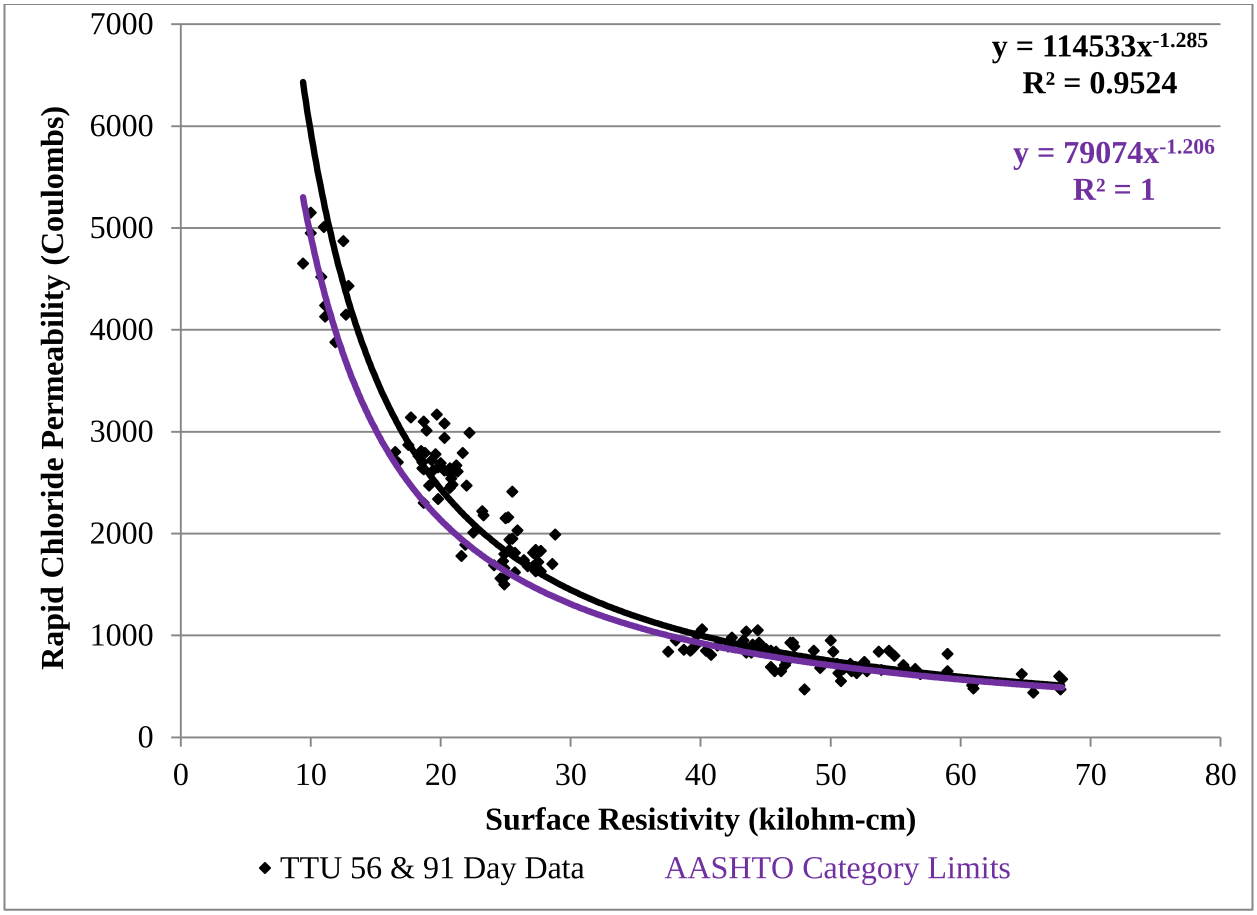

FIGURE 6.2: SR-RCP Correlation with only TTU Normally Moist Cured Results

TABLE 6.3: Statistical Comparisons of Data and Equations in Figure 6.2

Data Sets to be Compared	**|T statistic|**	**Statistical Difference?**	**How much higher/lower on average?**
TTU 56-Day and 91-Day Data and AASHTO Equation	9.792	Yes	AASHTO equation predictions are on average about 12% lower than TTU 56-Day and 91-Day RCP data

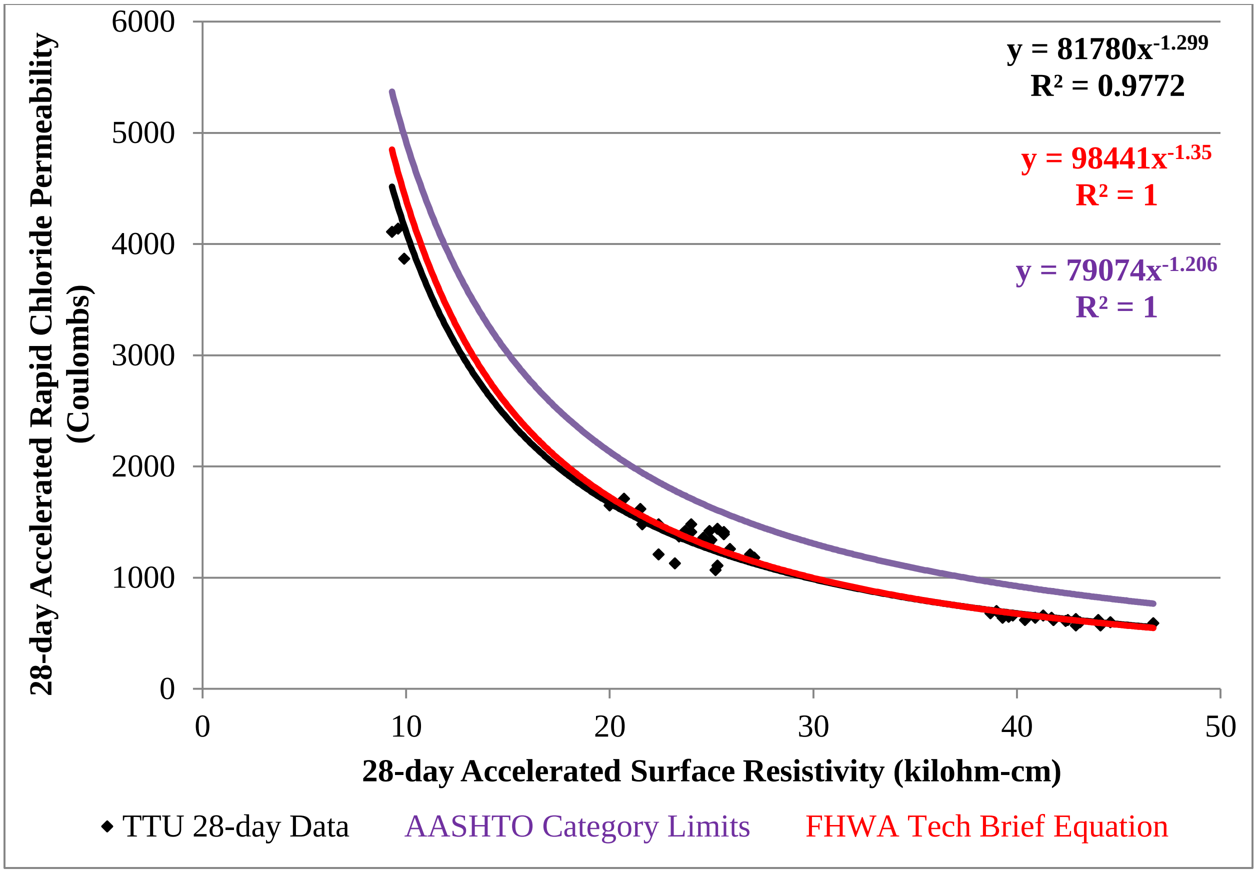

FIGURE 6.3: SR-RCP Correlation with only TTU Accelerated Moist Cured Results

TABLE 6.4: Statistical Comparisons of Data and Equations in Figure 6.3

Data Sets to be Compared	|T statistic|	Statistical Difference?	How much higher/lower on average?
TTU 28-Day Data and AASHTO Equation	14.524	Yes	AASHTO equation predictions are on average 29% higher than observed TTU 28-day data
TTU 28-Day Data and FHWA Tech Brief Equation	8.426	Yes	FHWA TB equation predictions on average about 3% higher than observed TTU 28-day data.

RCP Predictions

Figure 6.4 shows correlations between normally moist cured 56 and 91-day RCP results with 28-day accelerated moist cured results. Figure 6.4 contains only results from mixtures selected by TDOT for the current project. The high coefficients of determination ($R^2 > 0.9$) would seem to indicate that results at later ages can be predicted with 28-day accelerated moist cured results, considerably shortening the waiting time for chloride permeability information.

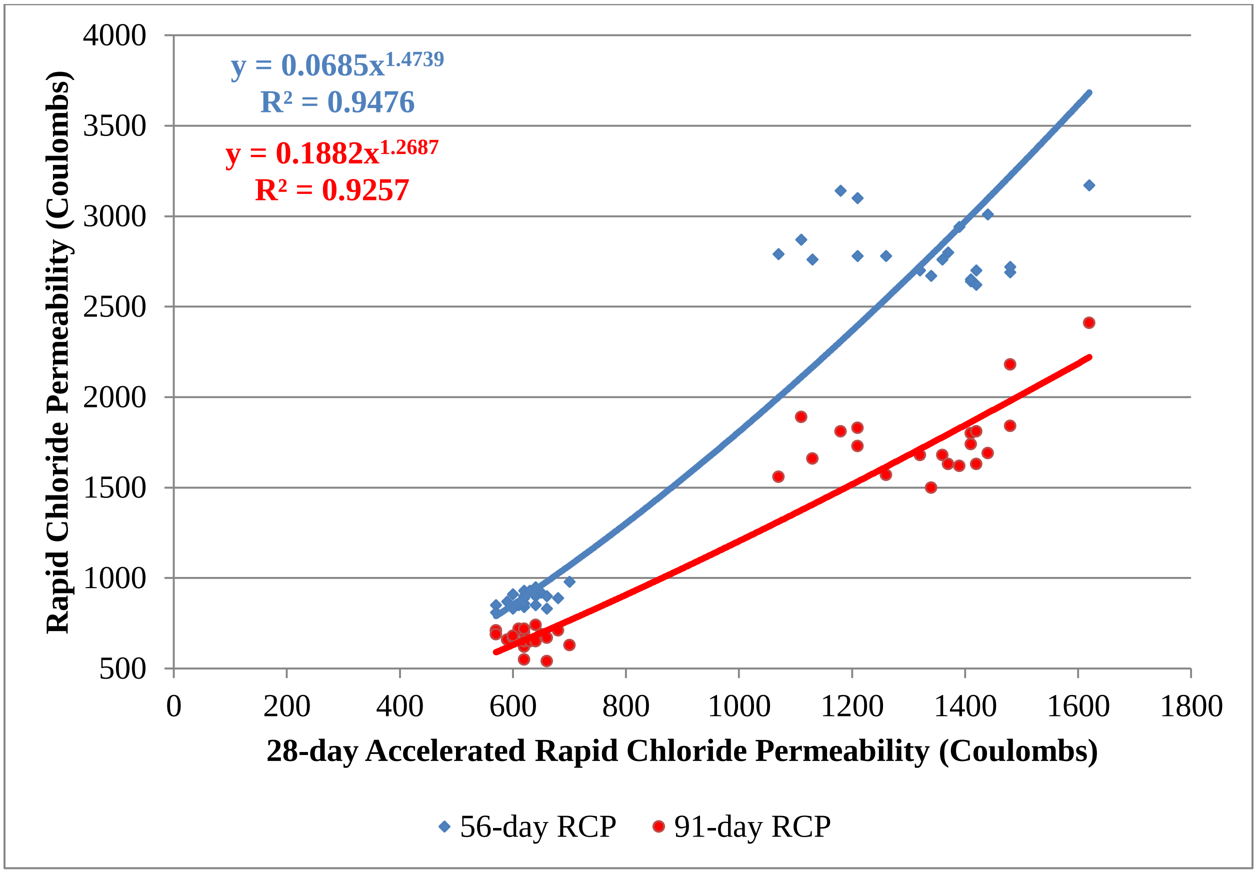

FIGURE 6.4: Prediction of 56 and 91-day RCP Results with 28-day Accelerated RCP Results

Figures 6.5 and 6.6 show correlations between normally moist cured 91-day RCP results with 56-day normally moist cured RCP results for mixtures selected by TDOT for the current project and all available TTU results, respectively. The high coefficients of determination ($R^2 > 0.9$) from both plots would seem to indicate 91-day RCP results can be predicted with 56-day RCP results, considerably shortening the waiting time for chloride permeability information. However, in the past TDOT M&T management has been more interested in 56-day results than in 91-day results. Thus, Figures 6.5 and 6.6 were included primarily to demonstrate the capability if TDOT M&T management became more interested in 91-day RCP results. It is interesting to note that 20 additional pairs of points only slightly altered the prediction equation and correlation coefficient.

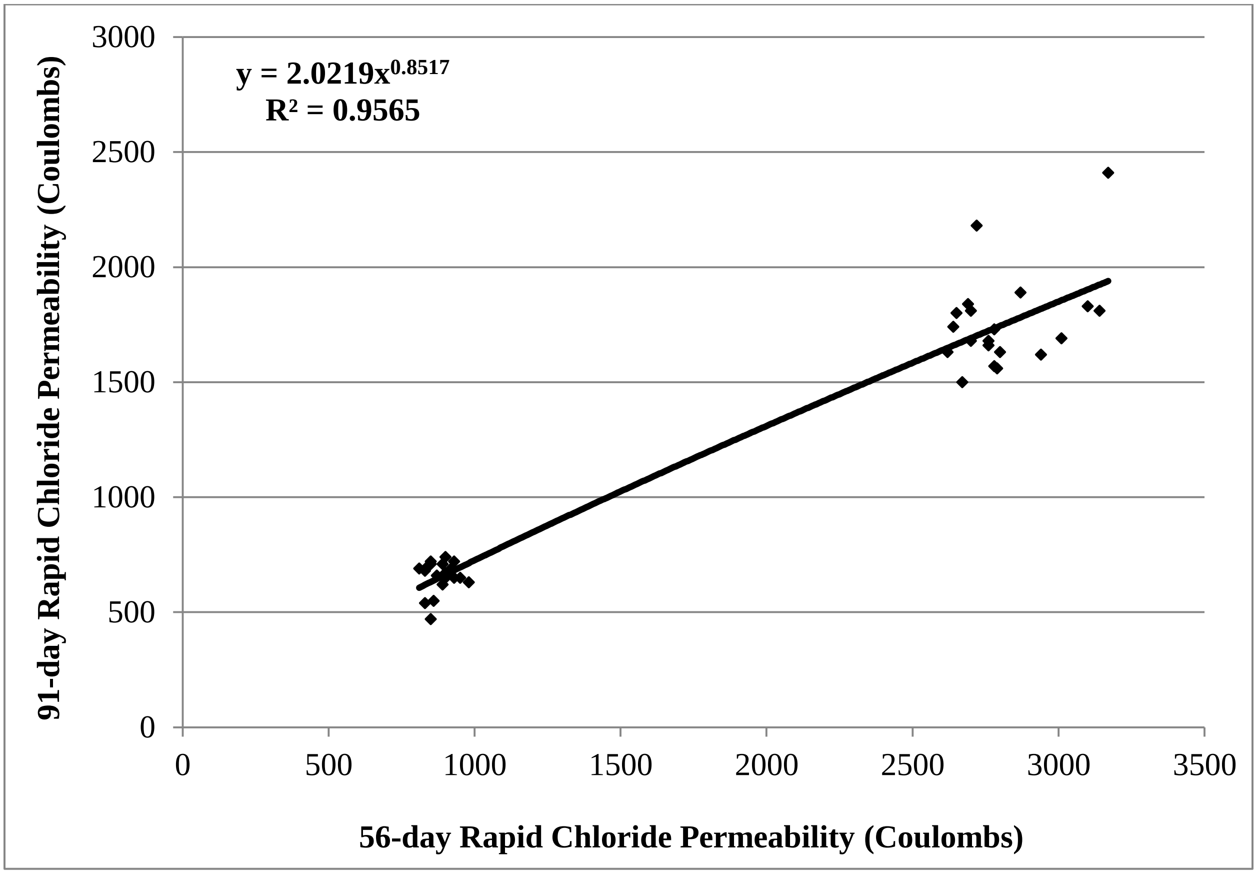

FIGURE 6.5: Prediction of 91-day RCP Results with 56-day RCP Results from the Current Project

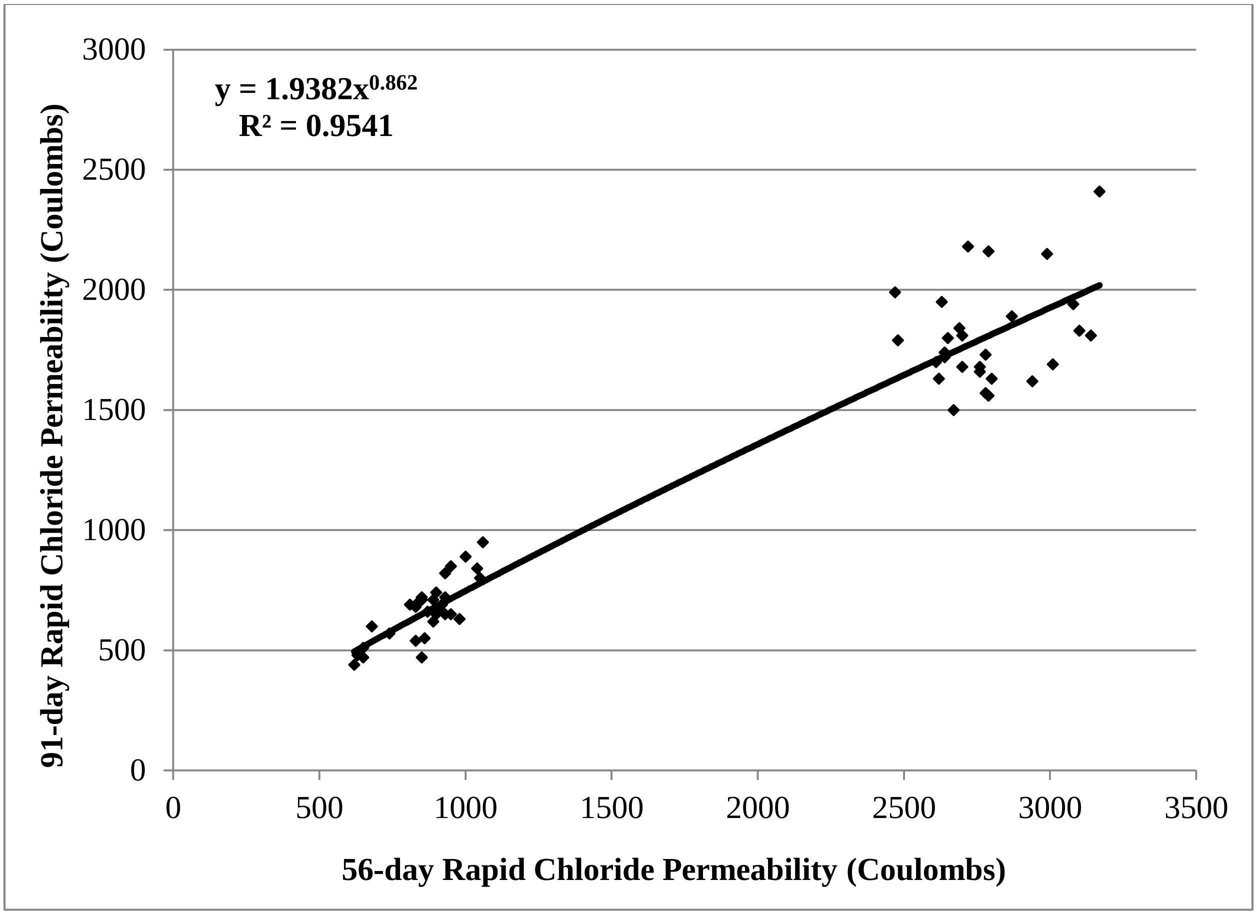

FIGURE 6.6: Prediction of 91-day RCP Results with All Available TTU 56-day RCP Results

Statistical Comparison of Predicted and Measured RCP Values

Table 6.5 shows a statistical comparison between predicted and measured RCP values. Complete predicted values and measured RCP results are shown in Appendices AH, AI, and AJ.

TABLE 6.5: Statistical Comparisons of Predicted and Measured RCP Values

Data Sets to be Compared	|T statistic|	Statistical Difference?	How much higher/lower on average?
56-day Prediction Equation based on TDOT 28-day Accelerated Results and 56-day Measured Results	0.53	No	Predicted 56-day RCP values are on average approximately 2% lower than the measured 56-day RCP values
91-day Prediction Equation based on TDOT 28-day Accelerated Results and 91-day Measured Results	0.77	No	Predicted 91-day RCP values are on average approximately 2% lower than the measured 91-day RCP values
91-day Prediction Equation based on 56-day TDOT Results and 91-day Measured Results	0.72	No	Predicted 91-day RCP values are on average 1.7% lower than the measured 91-day RCP values
91-day Prediction Equation based on 56-day All Available TTU Results and 91-day Measured Results	0.19	No	Predicted 91-day RCP values are on average 0.2% lower than the measured 91-day RCP values

SR Predictions

Figures 6.7 and 6.8 show correlations between normally moist cured 56 and 91-day SR results with 28-day accelerated moist cured and normally moist cured SR results, respectively. Figures 6.7 and 6.8 contain results only from mixtures selected by TDOT for the current project. Figure 6.9 shows correlations between normally moist cured 56 and 91-day SR results with 28-day normally moist cured SR results using all available TTU results. The high coefficients of determination ($R^2 > 0.9$) indicates that results at later ages can be predicted with either 28-day accelerated moist cured or 28-day normally moist cured results, considerably shortening the waiting time for chloride permeability information.

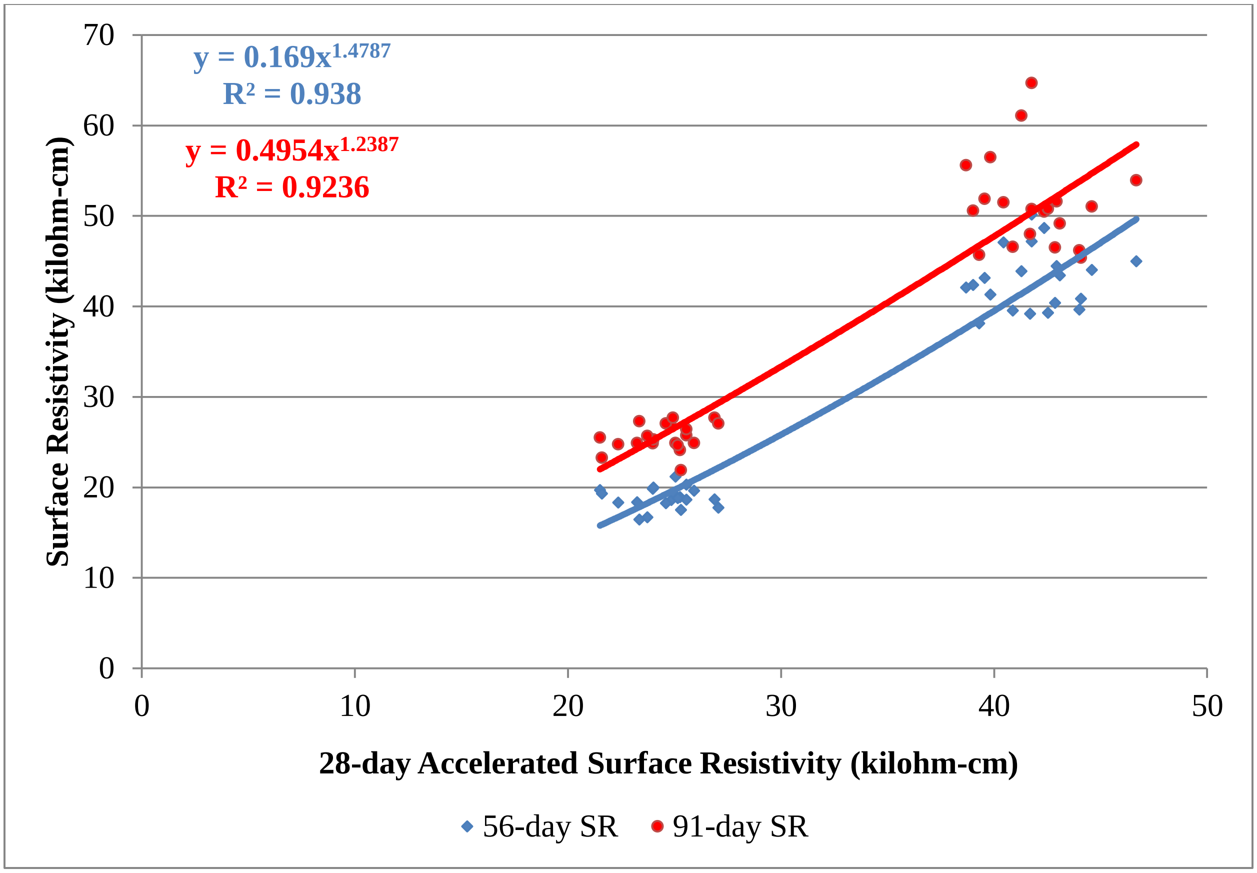

FIGURE 6.7: Prediction of 56 and 91-day SR Results with 28-day Accelerated SR Results

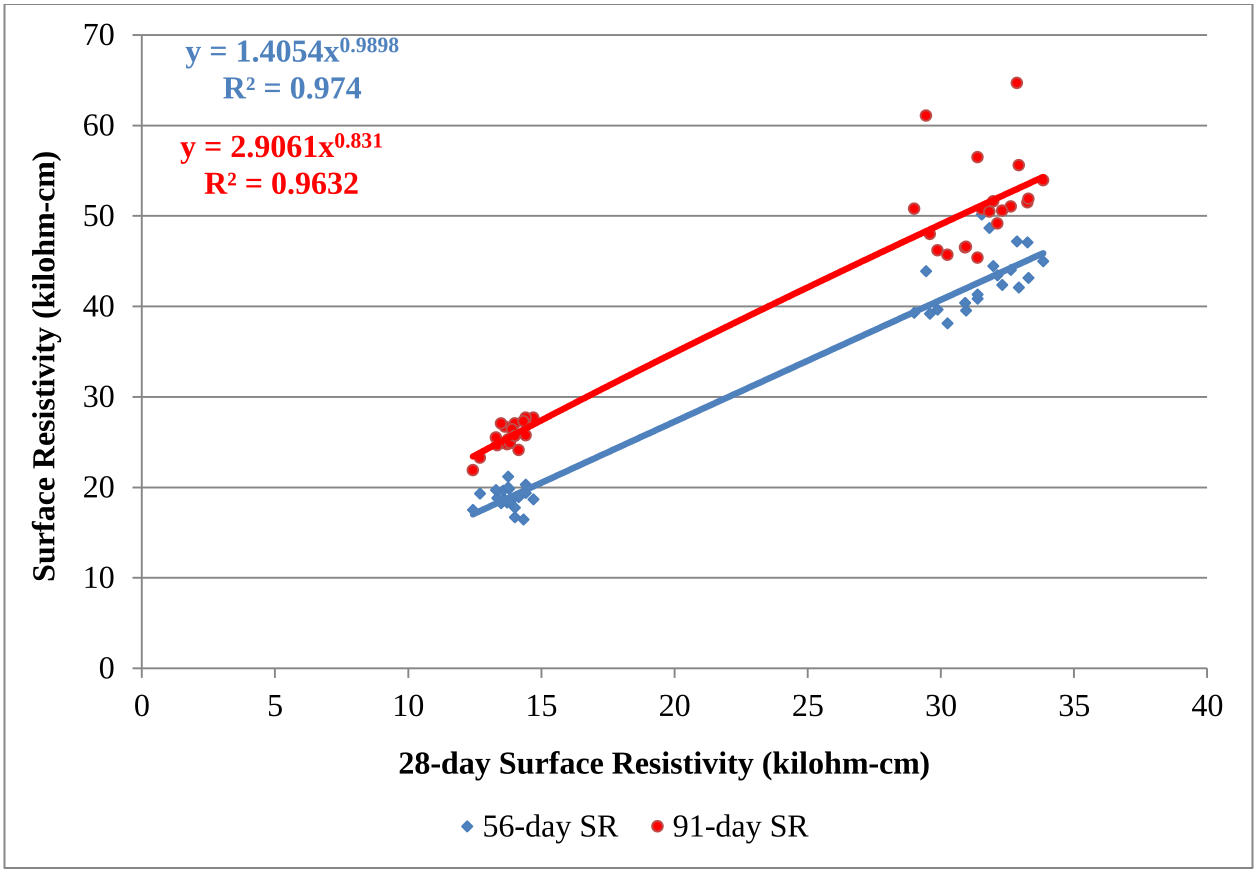

FIGURE 6.8: Prediction of 56 and 91-day SR Results with TDOT 28-day Normally Moist Cured SR Results

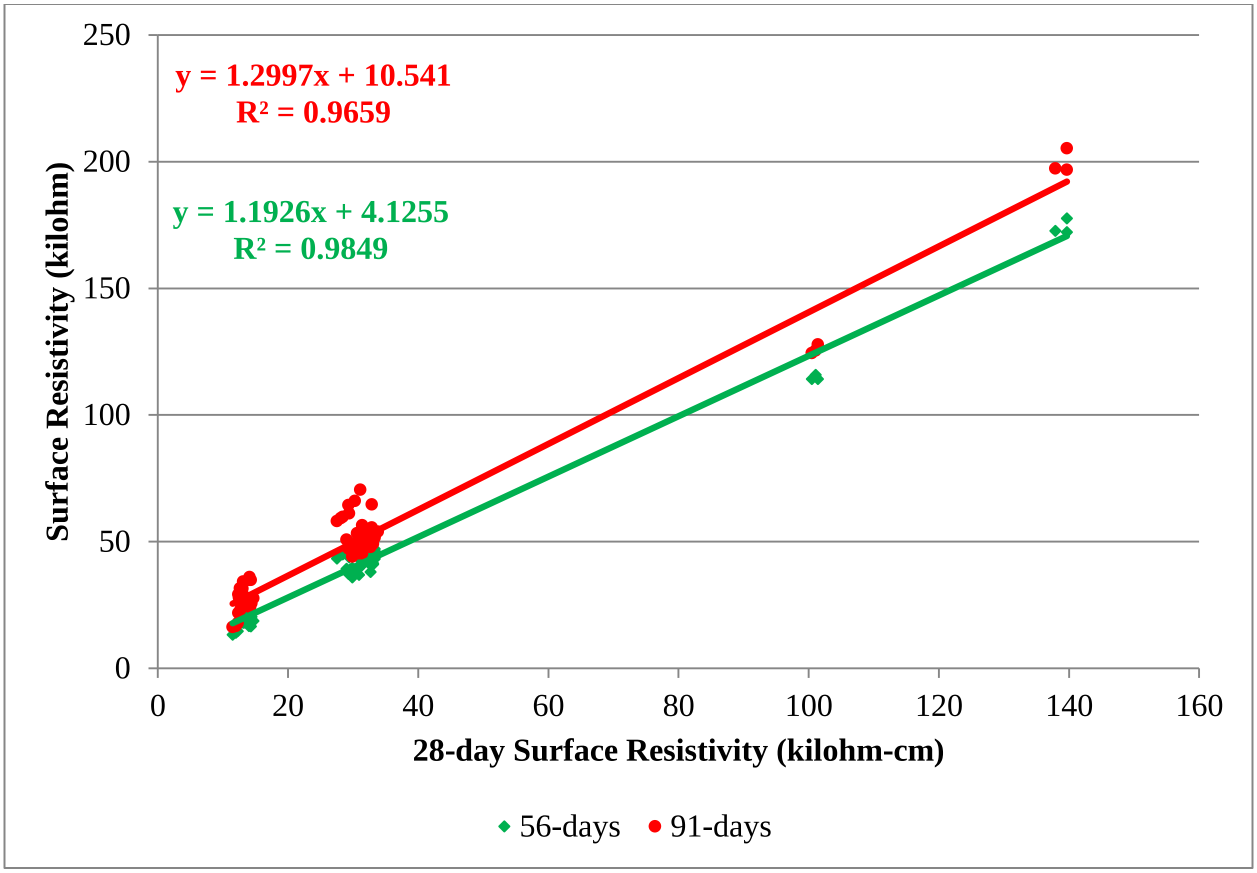

FIGURE 6.9: Prediction of 56 and 91-day SR Results with All Available TTU 28-day Normally Moist Cured SR Results

Figures 6.10 and 6.11 show correlations between normally moist cured 91-day SR results with 56-day normally moist cured SR results for mixtures selected by TDOT for the current project and all available TTU results, respectively. The high coefficients of determination ($R^2 > 0.9$) from both plots would seem to indicate that 91-day SR results could be predicted with 56-day SR results, considerably shortening the waiting time for chloride permeability information. However, in the past TDOT M&T management has been much more interested in 56-day results than 91-day results. Thus, Figures 6.10 and 6.11 were included primarily to demonstrate the capability if TDOT M&T management became more interested in 91-day SR results. Unlike RCP, the additional 39 pairs of points altered the type of prediction equation and the correlation coefficient.

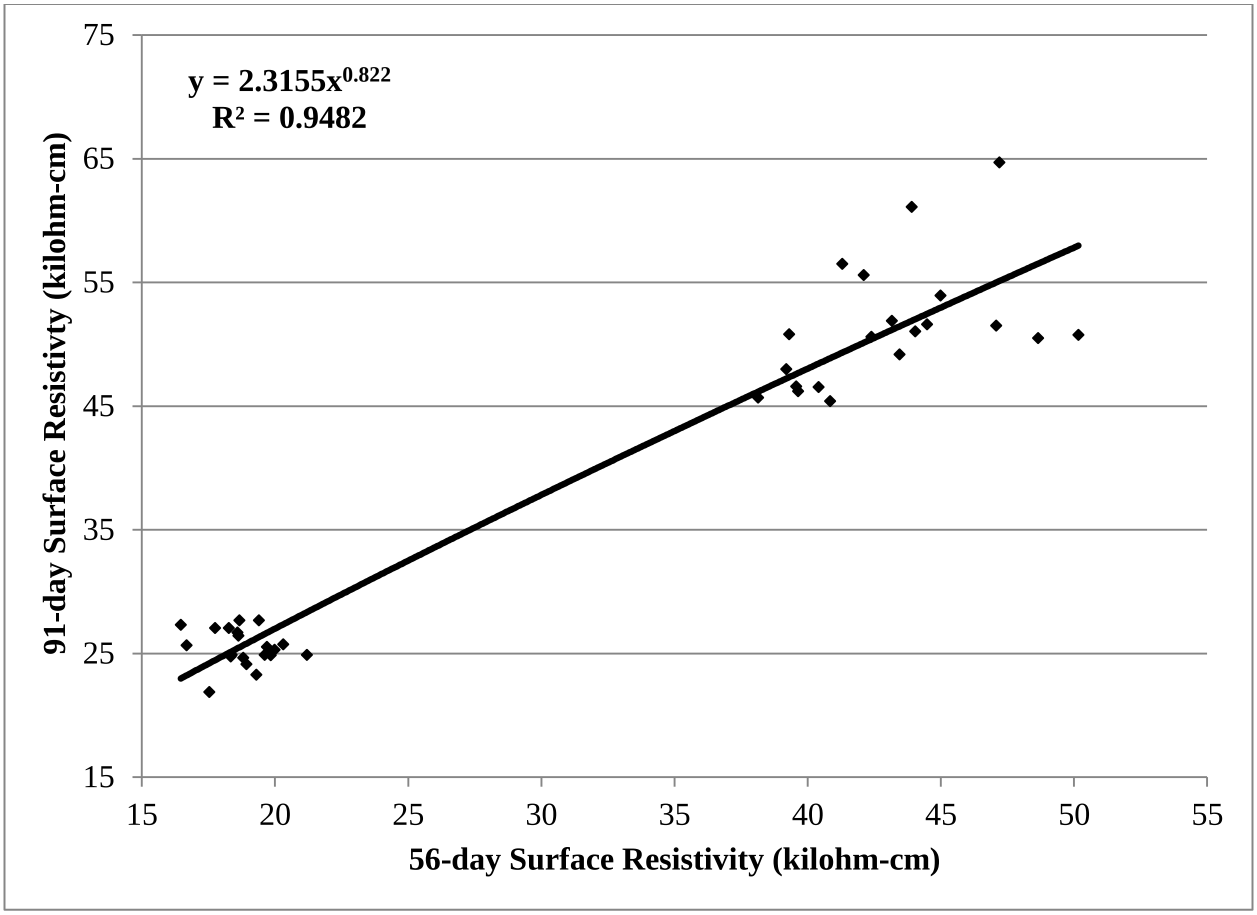

FIGURE 6.10: Prediction of 91-day SR Results with 56-day SR Results from the Current Project

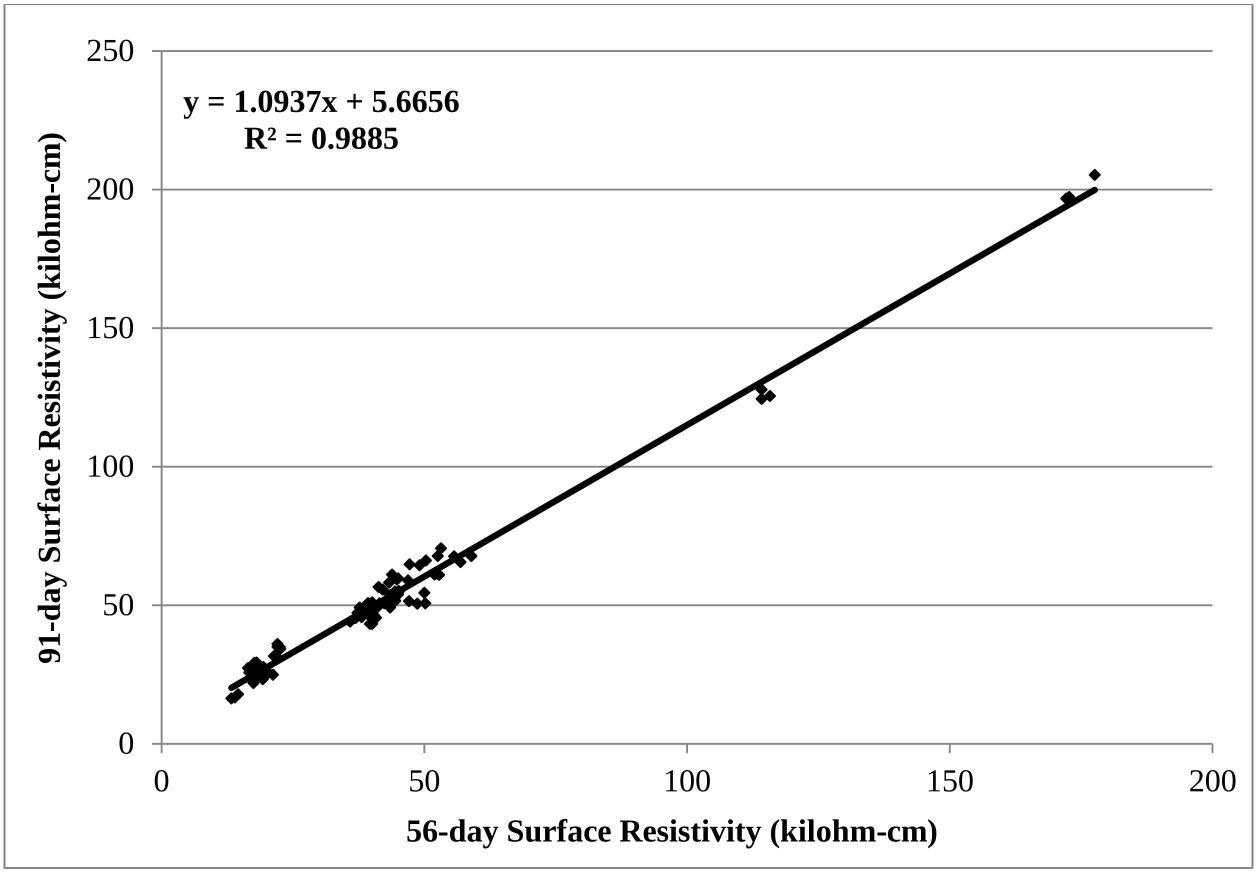

FIGURE 6.11: Prediction of 91-day SR Results with All Available TTU 56-day SR Results

Statistical Comparison of Predicted and Measured SR Values

Table 6.6 shows the statistical comparison of predicted and measured SR values. Complete predicted values and measured SR results are shown in Appendices AK, AL, and AM.

TABLE 6.6: Statistical Comparisons of Predicted and Measured SR Values

Data Sets to be Compared	|T statistic|	Statistical Difference?	How much higher/lower on average?
56-day Prediction Equation based on TDOT 28-day Accelerated Results and 56-day Measured Results	0.749	No	On average predicted 56-day SR values are 2.8% higher relative to the observed 56-day SR values
91-day Prediction Equation based on TDOT 28-day Accelerated Results and 91-day Measured Results	0.946	No	On average predicted 91-day SR values are 2.6% higher relative to the measured 91-day SR values
56-day Prediction Equation based on TDOT 28-day Results and 56-day Measured Results	0.172	No	On average predicted 56-day SR values are 0.6% lower relative to the measured 56-day SR values
91-day Prediction Equation based on TDOT 28-day Results and 91-day Measured Results	0.678	No	On average, predicted 91-day SR values are 0.6% higher relative to the measured 91-day SR values
56-day Prediction Equation based on All Available TTU 28-day Results and 56-day Measured Results	0.111	No	On average, predicted 56-day SR values are 0.1% higher relative to the measured 56-day SR values
91-day Prediction Equation based on All Available TTU 28-day Results and 91-day Measured Results	0.002	No	On average, predicted 91-day SR values are 0.002% lower than measured 91-day SR values
91-day Prediction Equation based on 56-day TDOT Results and 91-day Measured Results	0.806	No	On average, predicted 91-day SR values are 1.5% higher relative to the measured 91-day SR values
91-day Prediction Equation based on 56-day All Available TTU Results and 91-day Measured Results	0.005	No	On average, predicted 91-day SR values are 0.003% higher relative to measured 91-day SR values

Choosing a Test Method

Correlations

Table 6.7 shows some correlations between SR and RCP results for the same mixture at the same age. The correlations presented are from both literature and current experimentation. The correlations seem to be strong (close to or above 0.9). The test methods both purport to be evaluating the concrete's resistance to the flow of chloride ions. Both test methods use electric current (charge transmitted or resistance) to evaluate concrete resistance to chloride ion flow. Therefore, the choice of which method to use should be first based on the precision of the test methods.

TABLE 6.7: Comparison of SR-RCP Correlation Coefficients

Correlation	Source	Equation	Coefficient of Determination
Category Limits	AASHTO Test Methods	$RCP = 79074(SR)^{-1.206}$	0.9999
Provided Data	FHWA TF Lab	$RCP = 98441(SR)^{-1.35}$	0.9200
Provided Data	LTRC	$RCP = 39647(SR)^{-0.944}$	0.8922
All Available TTU Data	TTU Data	$RCP = 99584(SR)^{-1.271}$	0.8944
91 days	TTU Data	$RCP = 125451(SR)^{-1.316}$	0.9168
56 days	TTU Data	$RCP = 104446(SR)^{-1.253}$	0.9601
56+91 days	TTU Data	$RCP = 114533(SR)^{-1.285}$	0.9524
28-day Accelerated	TTU Data	$RCP = 81780(SR)^{-1.299}$	0.9772

Variability

A comparison of AASHTO test methods clearly indicates that SR has a lower single operator (6.3 vs. 12.3%) and multi-laboratory precision (12.5 vs. 18.0%). Table 6.8 shows comparisons between SR and RCP variability for the same mixture at the same age. The comparison winners of a pairing (substantially lower variability) are shown in italics. In three of the six cases, SR won two while RCP won one. In the other three of the six cases, there was no clear winner. Therefore, the choice of which method is better should not be primarily based on precision, but other criteria should have predominance.

TABLE 6.8: Comparison of SR and RCP Variability

Age of Test	**Mixture**	**Test Method**	**COV (%)**	**AASHTO Allowable Single Operator COV %**
28-day Accelerated	Class D 80/20	RCP	10.7	12.3
28-day Accelerated	Class D 80/20	SR	*6.3*	6.3
28-day Accelerated	50/35/15	RCP	5.3	12.3
28-day Accelerated	50/35/15	SR	5.0	6.3
56-day	Class D 80/20	RCP	6.0	12.3
56-day	Class D 80/20	SR	6.2	6.3
56-day	50/35/15	RCP	*5.1*	12.3
56-day	50/35/15	SR	7.8	6.3
91-day	Class D 80/20	RCP	12.1	12.3
91-day	Class D 80/20	SR	*5.9*	6.3
91-day	50/35/15	RCP	10.4	12.3
91-day	50/35/15	SR	9.8	6.3

Logistics

Table 6.9 shows comparisons between SR and RCP logistics. SR dominated the logistical comparison winning every individual category.

TABLE 6.9: Comparison of SR and RCP Logistics

Parameter	RCP	SR	Advantage
Initial Cost	Approx. $ 12,000	Approx. $ 3,000	SR
Recurring Costs	Chemicals, Epoxy	None	SR
Data Availability	2 days	About 10 minutes	SR
Time to Conduct	6 hours	About 10 minutes	SR
Preparation Time	About 1.5 days	About 15 minutes	SR
Clean Up Time	2 hours	Minutes	SR
Safety / Environmental Regulations	• Specimen Sawing • Chemical Storage	None	SR
Sample Reuse	No	Yes	SR
Technician Training	Considerable	Minimal	SR

Summary

Table 6.10 shows a summary of the comparisons between SR and RCP. SR is the clear choice, winning four of the six individual categories as well never losing in a logistical category.

TABLE 6.10: Summary Comparison of SR and RCP

Parameter	Advantage
Accuracy	Not Known
Variability (Precision)	Slight Edge SR (AASHTO Allowable)
Cost	Clearly SR (more than 4:1)
Time	Clearly SR (minutes vs days)
Ease of Operation	Clearly SR
Safety	SR (no chemicals or sawing)
Overall	Clearly SR

Choosing a Curing Regime

Investigating the Ambiguity of Accelerated Curing

The literature is somewhat ambiguous about what normally cured age is best associated with accelerated curing. Ozyildirim of the Virginia Transportation Research Council (who developed the method) says it gives results equivalent to 6 months of standard curing in TRR 1610 (26). HPC Bridge Views Issue 67 May/June 2011 (71) states that accelerated curing produces results equivalent to 90 days of standard curing. Unfortunately, the TDOT D-LP survey of state DOTs revealed that five states use accelerated curing in lieu of 56-day testing.

The research team attempted to solve the mystery with data from the current project. Figure 6.12 shows normally cured mean SR values plotted against time for both TDOT selected mixtures. Each point on the plot represents 20 results. Linear regression lines were also determined for each TDOT selected mixture. Using the linear regression equations and the SR results from each TDOT selected mixture, a “time” was calculated for each accelerated curing result. The “times” calculated were averaged and are shown in Figure 6.13. The average “times” for TDOT Class D with 20% Class F fly ash and the 50/35/15 mixture were 85.2 and 57.9 days, respectively.

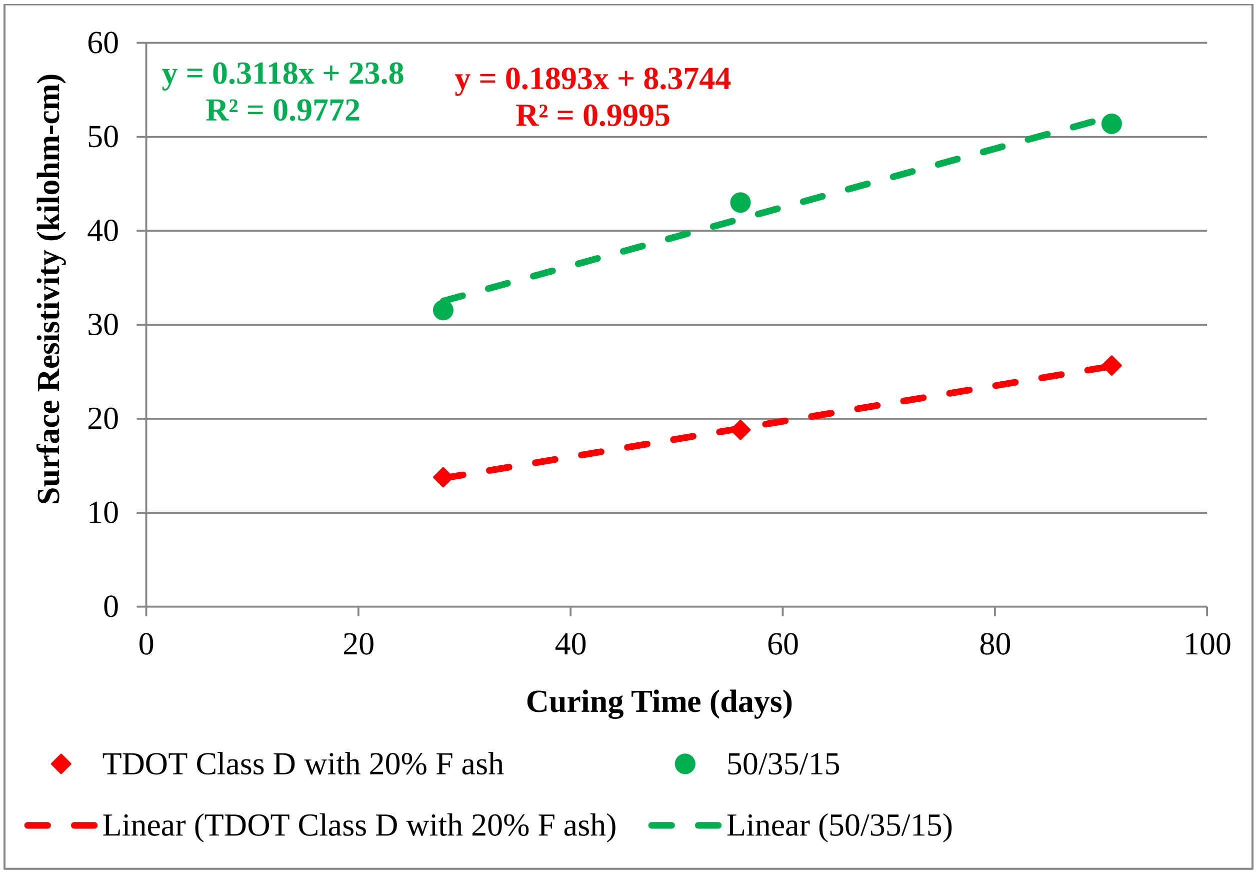

FIGURE 6.12: Mean Normally Cured SR Result vs. Curing Time

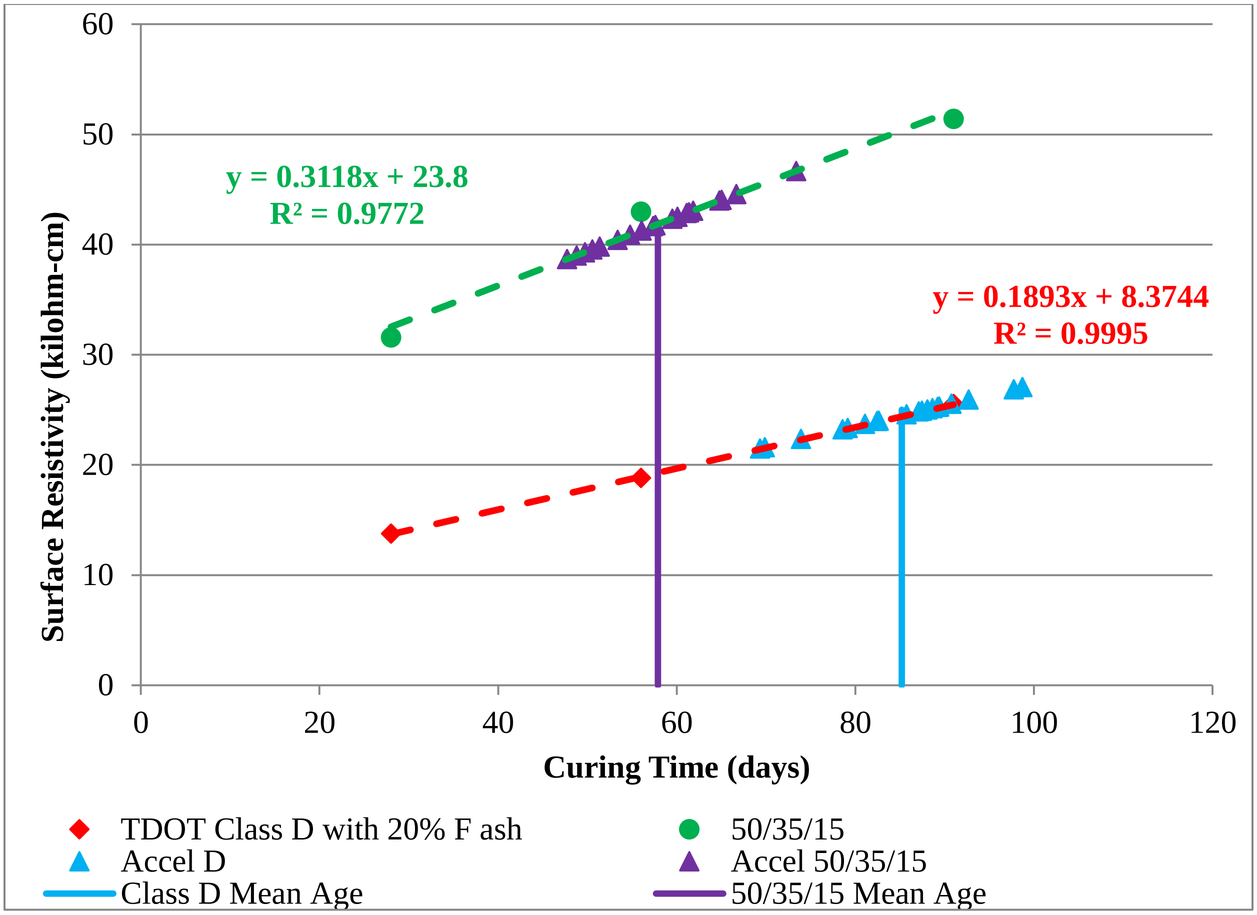

FIGURE 6.13: Mean Time Associated with Accelerated Curing of TDOT Selected Mixtures

The two TDOT selected mixtures had extensive similarities. Table 6.11 shows the similarities and differences between the TDOT selected mixtures. The primary difference between the two mixtures was in the SCMs. It seems that the normal curing time associated with accelerated curing is at least a function of the amount and type of SCMs. Unfortunately, the extensive similarities in the two mixtures selected precluded the research team from evaluating other factors that might affect the normal curing time associated with accelerated curing.

TABLE 6.11: **Comparison of TDOT Selected mixtures**

Parameter	Similarity or Difference in TDOT Selected Mixtures
w/cm	Both 0.37
Design air content	Both 7%
Total cementing materials content	Both 620-lbs/CY
Type and Brand of PC	Same
Class F fly ash	Same
Slag	Different one contained no slag
PC replacement with fly ash percentage	Similar 15 vs. 20%
PC replacement with slag percentage	Different 0 vs 35%
Coarse aggregate	Same sample from same quarry
Coarse aggregate amount	Similar 1857 vs. 1854-lbs/CY SSD
Fine aggregate	Same sample from same quarry
Fine aggregate amount	Same 1118-lbs/CY
Air entraining agent	Same brand different dosage
Water reducer	Same brand different dosage
High range water reducer	Same brand different dosage

Value as a Predictor of Later Age Results

Table 6.12 shows correlations between accelerated and normally cured 28-day SR results with 56 and 91-day normally cured SR results for the same mixture. The correlations are strong (all $R^2 > 0.92$). The correlations presented indicate that accelerated curing does not correlate with later age results as well as normal curing. This competition is too close to call and therefore, the choice of curing method to use should be based on other criteria.

TABLE 6.12: Comparison of Accelerated and Normal Cured 28-day Results Correlations with 56 and 91-day Normally Cured Results

Predictor	Attempting to Predict (days)	Coefficient of Determination
28-day Accelerated Curing	56	0.938
28-day Normal Curing	56	0.974
28-day Accelerated Curing	91	0.925
28-day Normal Curing	91	0.963

Logistics

Table 6.13 shows comparisons between accelerated and normal curing logistics. Normal curing dominated the logistical comparison by not losing in any individual category.

TABLE 6.13: Comparison of Accelerated and Normal Cured Logistics

Parameter	Accelerated	Normal	Advantage
Water Heater	Larger and more expensive	Smaller and less expensive	Normal
Water Circulation	Pump, PVC pipe and hoses	Pump and hoses	Slight Edge Normal
Insulation	Required	Not needed or minimal	Normal
Battery Backup	Higher capacity more expensive	Lower capacity less expensive	Normal
Response Time (before falling out of temp range)	2 to 3 hours	Much longer (close to lab temp)	Normal
Monitoring Equipment	Computer, data acquisition package and thermocouples	Computer, data acquisition package and thermocouples	None
Power Consumption	Higher	Lower	Normal

Summary

Table 6.14 shows a summary of the comparisons between accelerated and normal curing. Normal curing is the clear choice winning four of the six individual categories as well never losing in a category.

TABLE 6.14: Summary of Comparison of Accelerated and Normal Curing

Parameter	Advantage
Ambiguity (what “time” or “age”)	Normal Curing
Predicting Later Values (Correlations)	Too close to call
Cost	Normal Curing
Time	Same
Ease of Operation	Normal Curing
Fail Safety (Response Time)	Normal Curing
Overall	Normal Curing

Calculating What to Specify

If SR is selected as the preferred test method by TDOT M&T Division management, the next logical question would be what 28-day SR should be specified as the equivalent to the 1200 Coulombs at 56 days selected in previous TDOT research. The first step in answering that question is to convert the 56-day RCP value to a 56-day SR value. Table 6.15 shows several correlations between a 56-day 1200 Coulombs for RCP and 56-day SR.

TABLE 6.15: Conversions from 1200-Coulombs @ 56-days RCP to Equivalent 56-day SR

Correlation	Equation	SR Result (kilohm-cm)
AASHTO Categories	$SR = 11494(RCP)^{-0.829}$	32.2
TTU All Data	$SR = 4724.2(RCP)^{-0.704}$	32.1
TTU 56-day	$SR = 8006.4(RCP)^{-0.767}$	34.8
UT All Data	$SR = 3016(RCP)^{-0.654}$	29.2
UT 56-day	$SR = 2834.6(RCP)^{-0.656}$	27.1

The AASHTO and TTU All Data correlations produced very similar SR results. These two results seem to be in the middle with TTU 56-day being less conservative and UT being more conservative. Since an AASHTO correlation is easily accessible and easy to defend, the research team recommends it.

The next step is to convert the 56-day SR value to a 28-day SR value. Table 6.16 shows several conversions from a 56-day SR of 32.2 to a 28-day SR value based on TTU prediction equations presented earlier.

TABLE 6.16: Conversions from 56-day SR to 28-day SR

Correlation	SR28 Accelerated Cured TDOT Data Only (kilohm-cm)	SR28 Normal Cured All TTU Data (kilohm-cm)	SR28 Normal Cured TDOT Data Only (kilohm-cm)
Value	34.8	22.9	23.6

The research team recommends a SR of 24 for a 28-day specification with normal curing. However, an SR of 35 with accelerated curing would also be a reasonable 28-day specification. Recall that accelerated curing for both 80PC/20F and 50PC/35SL/15F indicated that accelerated curing produces an equivalent normal curing age greater than 56-days and therefore the accelerated curing SR is greater than the SR equivalent to RCP = 1200 Coulombs at 56-days.

CHAPTER 7 : CONCLUSIONS

The following conclusions can be drawn from the results obtained from this study:

Correlations

1. There is a strong relationship between SR and RCP results for the same mixture at the same age for all TTU data (202 points, $R^2 = 0.8944$).
2. There is a strong relationship between SR and RCP results for the same mixture at the same age for 56 and 91-day normally moist-cured TTU data (155 points, $R^2 = 0.9524$).
3. There is a strong relationship between SR and RCP results for the same mixture at the same age for 28-day accelerated TTU data (47 points, $R^2 = 0.9772$).
4. There are statistically significant differences between the TTU RCP data and the predictions given by the AASHTO Categories equation.
5. There are statistically significant differences between the TTU data and the predictions given by the LTRC equation.
6. There are statistically significant differences between the TTU RCP data and the predictions given by the FHWA TB equation.
7. There is a statistically significant difference between the TTU 56 and 91-day data and the predictions given by the AASHTO Categories equation.
8. There is a statistically significant difference between the TTU 28-day accelerated data and the respective predictions given by the AASHTO Categories equation and the FHWA TB equation.
9. The above significant observations, which are based on TTU data, lead to the conclusion that equations reported by national agencies may not transfer effectively elsewhere. Hence,

there is the need to either use them with caution or to develop equations locally that would more likely be better suited to the local environment.

SR Predictions

1. There is a strong relationship between 28-day accelerated SR results and SR for the same mixture at 56 days (R^2 = 0.938) and 91 days (R^2 = 0.9236) for TDOT project data (40 points per age).
2. There is a strong relationship between 28-day normal moist-cured SR results and SR for the same mixture at 56 days (R^2 = 0.974) and 91 days (R^2 = 0.9632) for TDOT project data (40 points per age).
3. There is a strong relationship between 28-day normal moist-cured SR results and SR for the same mixture at 56 days (R^2 = 0.9849) and 91 days (R^2 = 0.9659) for all TTU data (79 points per age).
4. There is a strong relationship between 56-day SR results and SR for the same mixture at 91 days (R^2 = 0.9482 for 40 TDOT points) and (R^2 = 0.9885 for 79 TTU points).
5. Overall, the results of the statistical analysis here lead to the conclusion that the measured SR of early age specimens is a very good predictor of the SR to be attained at a much later age. This finding has the potential to reduce agency time and cost associated with durability tests.

RCP Predictions

1. There is a strong relationship between 28-day accelerated RCP results and RCP for the same mixture at the 56 days (R^2 = 0.9476) and 91 days (R^2 = 0.9257) for TDOT project data (40 points per age).

2. There is a strong relationship between 56-day RCP results and RCP for the same mixture at 91 days ($R^2 = 0.9565$ for 40 TDOT points) and ($R^2 = 0.9541$ for 60 TTU points).
3. Again, overall, the results of the statistical analysis here lead to the conclusion that the measured RCP of early age specimens is a very good predictor of the RCP to be attained at a much later age. This finding has the potential to reduce agency time and cost associated with the conduct of rapid chloride permeability tests.

Test Method

1. SR is strongly preferred over RCP as a test method because of the cost and the logistical reasons aforementioned.

Curing Method

1. The results obtained from normally-cured 28-day SR specimens correlate to later age SR results just as well if not slightly better than the SR results of 28-day specimens cured in an accelerated manner (7 days @ 73°F and 21 days @ 100°F).
2. The normal moist-cured age equivalent to that of accelerated moist-cured is dependent on the composition of the PC/SCM matrix.
3. Normal curing of SR specimens is strongly preferred over accelerated curing for logistical reasons.

CHAPTER 8 : RECOMMENDATIONS

Based on the results and analysis, the research team recommends the following:

1. Use SR (AASHTO TP 95-11) instead of RCP (AASHTO T 277-07).
2. Use normal curing instead of accelerated curing.
3. Specify SR of 24 minimum at 28-days with normal curing. Specify SR of 35 minimum with 28-day accelerated curing.
4. Accumulate more SR and/or RCP data on mixtures containing:
    A. No SCM (recent outage)
    B. Class C fly ash
    C. Higher percentage replacements of Class F fly ash (~25%)
    D. Silica fume
    E. Metakaolin
5. Accumulate more SR and/or RCP data on mixtures:
    A. With coarse aggregates other than that used in this study
    B. With fine aggregates other than that used in this study
    C. With lightweight coarse and/or fine aggregates
    D. With w/cm ratios other than 0.37
    E. With fine aggregate percentages other than 38

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APPENDICES

Appendix A

Validation Batches 28-Day Compressive Strength Data

TABLE A.1: TDOT Class D Validation 28-Day Compressive Strength

ID #	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Range (psi)	Compressive Strength (psi)
D-1	1/23/2014	5137	5180	43	5160
D-2	1/30/2014	5062	4802	260	4930
D-3	1/30/2014	5017	5137	120	5080
D-4	2/4/2014	5452	5427	25	5440
D-5	2/4/2014	5438	5321	117	5380

TABLE A.2: 50/35/15 Validation 28-Day Compressive Strength

ID #	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Range (psi)	Compressive Strength (psi)
S-1	5/7/2014	6303	6431	128	6370
S-2	5/7/2014	6426	6592	166	6510
S-3	5/8/2014	6281	6277	4	6280
S-4	5/8/2014	6181	6179	2	6180
S-5	5/8/2014	5828	6221	393	6030

Appendix B

Validation Batches 56-Day Compressive Strength Data

TABLE B.1: TDOT Class D Validation 56-Day Compressive Strength

ID #	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Range (psi)	Compressive Strength (psi)
D-1	1/23/2014	5935	5672	263	5800
D-2	1/30/2014	5611	5840	329	5730
D-3	1/30/2014	5589	5974	385	5780
D-4	2/4/2014	6015	6033	18	6020
D-5	2/4/2014	6073	5999	74	6040

TABLE B.2: 50/35/15 Validation 56-Day Compressive Strength

ID #	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Range (psi)	Compressive Strength (psi)
S-1	5/7/2014	7104	7098	6	7100
S-2	5/7/2014	6903	7030	127	6970
S-3	5/8/2014	7107	7150	43	7130
S-4	5/8/2014	6747	6712	35	6730
S-5	5/8/2014	6846	6772	74	6810

Appendix C

Validation Batches 28-Day Static Modulus of Elasticity Data

TABLE C.1: TDOT Class D Validation 28-Day Static Modulus of Elasticity

ID #	Cast Date	Run 1 (psi)	Run 2 (psi)	Range (psi)	Static Modulus of Elasticity (psi)
D-1	1/23/2014	4300000	4350000	50000	4350000
D-2	1/30/2014	4250000	4220000	30000	4250000
D-3	1/30/2014	4390000	4390000	0	4400000
D-4	2/4/2014	4340000	4340000	0	4350000
D-5	2/4/2014	4320000	4320000	0	4300000

TABLE C.2: 50/35/15 Validation 28-Day Static Modulus of Elasticity

ID #	Cast Date	Run 1 (psi)	Run 2 (psi)	Range (psi)	Static Modulus of Elasticity (psi)
S-1	5/7/2014	4610000	4580000	30000	4600000
S-2	5/7/2014	4460000	4510000	50000	4500000
S-3	5/8/2014	4420000	4430000	10000	4450000
S-4	5/8/2014	4590000	4520000	70000	4550000
S-5	5/8/2014	4550000	4560000	10000	4550000

Appendix D

Validation Batches 56-Day Static Modulus of Elasticity Data

TABLE D.1: TDOT Class D Validation 56-Day Static Modulus of Elasticity

ID #	Cast Date	Run 1 (psi)	Run 2 (psi)	Range (psi)	Static Modulus of Elasticity (psi)
D-1	1/23/2014	4300000	4310000	10000	4300000
D-2	1/30/2014	4480000	4490000	10000	4500000
D-3	1/30/2014	4410000	4410000	0	4400000
D-4	2/4/2014	4410000	4350000	60000	4400000
D-5	2/4/2014	4390000	4300000	90000	4350000

TABLE D.2: 50/35/15 Validation 56-Day Static Modulus of Elasticity

ID #	Cast Date	Run 1 (psi)	Run 2 (psi)	Range (psi)	Static Modulus of Elasticity (psi)
S-1	5/7/2014	4570000	4570000	0	4550000
S-2	5/7/2014	4780000	4740000	40000	4750000
S-3	5/8/2014	4690000	4660000	30000	4650000
S-4	5/8/2014	5030000	5020000	10000	5050000
S-5	5/8/2014	Damaged			

Appendix E

Validation Batches 56-Day Hardened Concrete Absorption Data

TABLE E.1: TDOT Class D Validation 56-Day Absorption

ID #	Cylinder 1 (%)	Cylinder 2 (%)	Cylinder 3 (%)	Range (%)	Absorption (%)
D-1	5.63	5.41	5.44	0.22	5.5
D-2	5.27	5.29	5.53	0.26	5.4
D-3	5.54	5.36	5.67	0.31	5.5
D-4	5.28	5.05	5.3	0.25	5.2
D-5	5.33	5.49	5.24	0.25	5.4

TABLE E.2: 50/35/15 Validation 56-Day Absorption

ID #	Cylinder 1 (%)	Cylinder 2 (%)	Cylinder 3 (%)	Range (%)	Absorption (%)
S-1	5.45	5.50	5.57	0.12	5.5
S-2	5.05	5.36	5.44	0.39	5.3
S-3	5.52	5.50	5.43	0.09	5.5
S-4	5.50	5.50	5.83	0.33	5.6
S-5	5.31	5.28	5.2	0.11	5.3

Appendix F

SR-RCP Batches 28-Day Compressive Strength Data

TABLE F.1: TDOT Class D 28-Day Compressive Strength

ID #	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Cylinder 3 Result (psi)	Range (psi)	Compressive Strength (psi)
D-6	2/6/2014	5669	5426	5369	300	5490
D-7	2/6/2014	5891	5677	5763	214	5780
D-8	2/18/2014	5185	5169	5469	300	5270
D-9	2/18/2014	5122	5218	5074	144	5140
D-10	2/20/2014	5564	5835	5189	646	5530
D-11	2/20/2014	5521	5655	5667	146	5610
D-12	2/25/2014	5342	5032	5423	391	5270
D-13	2/25/2014	5460	5493	5516	56	5490
D-14	3/4/2014	5392	5446	5519	127	5450
D-15	3/4/2014	5447	5006	5241	441	5230
D-16	3/6/2014	5924	5768	5667	257	5790
D-17	3/6/2014	6051	5931	6073	142	6020
D-18	3/19/2014	5696	5309	5171	525	5390
D-19	3/19/2014	5163	5245	5486	323	5300
D-20	4/2/2014	5596	6154	5988	558	5910
D-21	4/2/2014	5722	5936	6008	286	5990
D-22	8/26/2014	4890	5135	4858	277	4960
D-23	8/26/2014	5143	5162	5292	149	5200
D-24	4/17/2014	5508	5463	5501	45	5490
D-25	4/17/2014	4930	4884	4941	57	4920

TABLE F.2: 50/35/15 28-Day Compressive Strength

ID #	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Cylinder 3 Result (psi)	Range (psi)	Compressive Strength (psi)
S-6	5/16/2014	6310	6535	5956	579	6270
S-7	5/16/2014	6490	6337	6485	153	6440
S-8	5/20/2014	6862	6728	6651	311	6750
S-9	5/20/2014	6725	6467	6681	258	6620
S-10	5/23/2014	6307	6563	6799	492	6560
S-11	5/23/2014	6643	6500	6469	174	6540
S-12	7/23/2014	6845	7758	7641	913	7420
S-13	7/23/2014	7049	7306	7468	419	7270
S-14	7/11/2014	7146	6912	6793	353	6950
S-15	7/11/2014	7366	7304	7037	362	7240
S-16	6/3/2014	6862	8044	7505	1182	7470
S-17	6/3/2014	6270	6503	6634	364	6400
S-18	6/5/2014	7263	6887	7038	376	7060
S-19	6/5/2014	6323	6343	6432	109	6370
S-20	6/10/2014	7281	6476	6992	805	6920
S-21	6/10/2014	7214	7407	6623	784	7080
S-22	6/12/2014	7327	7548	7022	526	7300
S-23	6/12/2014	7155	7433	7331	278	7310
S-24	7/9/2014	7057	7185	7078	128	7110
S-25	7/9/2014	6472	6905	6853	433	6740

Appendix G

SR-RCP Batches 28-Day Accelerated Compressive Strength Data

TABLE G.1: TDOT Class D 28-Day Accelerated Compressive Strength

ID #	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Cylinder 3 Result (psi)	Range (psi)	Compressive Strength (psi)
D-6	2/6/2014	6651	6479	6297	354	6480
D-7	2/6/2014	7039	7100	6833	267	6990
D-8	2/18/2014	6079	6020	6241	221	6110
D-9	2/18/2014	6011	6092	6184	173	6100
D-10	2/20/2014	6609	6469	6494	140	6520
D-11	2/20/2014	6207	6503	6716	509	6480
D-12	2/25/2014	6607	6267	5968	639	6280
D-13	2/25/2014	6389	6353	6491	138	6410
D-14	3/4/2014	6414	6025	6472	447	6300
D-15	3/4/2014	6092	5653	5473	619	5740
D-16	3/6/2014	6519	6377	6628	251	6510
D-17	3/6/2014	6875	6602	7098	496	6860
D-18	3/19/2014	6319	6449	6283	166	6350
D-19	3/19/2014	6030	5958	6194	236	6060
D-20	4/2/2014	6620	7154	6836	534	6870
D-21	4/2/2014	7197	7004	6473	724	6890
D-22	8/26/2014	5675	5959	5932	284	5860
D-23	8/26/2014	5747	5746	5636	111	5710
D-24	4/17/2014	6331	6313	6062	269	6240
D-25	4/17/2014	5687	5338	5854	516	5630

TABLE G.2: 50/35/15 28-Day Accelerated Compressive Strength

ID #	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Cylinder 3 Result (psi)	Range (psi)	Compressive Strength (psi)
S-6	5/16/2014	6817	7119	7302	485	7080
S-7	5/16/2014	7355	6875	6606	749	6950
S-8	5/20/2014	7337	7633	6973	656	7310
S-9	5/20/2014	7292	7157	7358	201	7270
S-10	5/23/2014	7938	7345	7770	593	7680
S-11	5/23/2014	6895	6531	7165	634	6860
S-12	7/23/2014	7452	8280	7950	828	7890
S-13	7/23/2014	7863	7527	8084	557	7830
S-14	7/11/2014	6993	7413	7521	528	7310
S-15	7/11/2014	7519	7849	7353	330	7570
S-16	6/3/2014	7424	7625	6430	1195	7160
S-17	6/3/2014	7547	7785	6893	892	7410
S-18	6/5/2014	7406	7830	8015	609	7750
S-19	6/5/2014	6406	6862	7249	843	6840
S-20	6/10/2014	7199	7330	7422	223	7320
S-21	6/10/2014	7362	7774	7652	412	7600
S-22	6/12/2014	7805	7751	7711	94	7760
S-23	6/12/2014	7854	7622	7800	232	7760
S-24	7/9/2014	7518	7922	7511	411	7650
S-25	7/9/2014	8176	7485	7728	691	7800

Appendix H

SR-RCP Batches 56-Day Compressive Strength Data

TABLE H.1: TDOT Class D 56-Day Compressive Strength

ID #	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Cylinder 3 Result (psi)	Range (psi)	Compressive Strength (psi)
D-6	2/6/2014	6170	6092	6168	76	6140
D-7	2/6/2014	6075	6139	6278	203	6160
D-8	2/18/2014	6012	5583	5961	429	5850
D-9	2/18/2014	5858	5925	5561	364	5780
D-10	2/20/2014	5959	6234	6371	412	6190
D-11	2/20/2014	5983	6625	6361	642	6320
D-12	2/25/2014	5880	5743	5851	137	5830
D-13	2/25/2014	6408	6228	6299	180	6310
D-14	3/4/2014	5397	6436	6459	1062	6100
D-15	3/4/2014	5569	5631	5835	266	5680
D-16	3/6/2014	6194	6301	6193	108	6230
D-17	3/6/2014	6949	6502	6845	447	6770
D-18	3/19/2014	6414	6370	5894	520	6230
D-19	3/19/2014	5958	5984	6234	276	6060
D-20	4/2/2014	6563	7133	7027	570	6910
D-21	4/2/2014	6818	6928	6977	159	6910
D-22	8/26/2014	5245	5580	5721	476	5520
D-23	8/26/2014	5503	5446	5512	72	5490
D-24	4/17/2014	6091	5849	5975	242	5970
D-25	4/17/2014	5610	5948	5886	338	5820

TABLE H.2: 50/35/15 56-Day Compressive Strength

ID #	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Cylinder 3 Result (psi)	Range (psi)	Compressive Strength (psi)
S-6	5/16/2014	6859	6734	6622	237	6740
S-7	5/16/2014	6840	6938	7129	289	6970
S-8	5/20/2014	6600	6822	6908	308	6780
S-9	5/20/2014	6834	6996	6778	218	6870
S-10	5/23/2014	7489	7918	8154	665	7850
S-11	5/23/2014	7192	6997	7015	195	7070
S-12	7/23/2014	7230	7666	6956	710	7280
S-13	7/23/2014	7623	7022	7538	601	7390
S-14	7/11/2014	7209	7339	7286	139	7280
S-15	7/11/2014	7790	7947	7832	157	7860
S-16	6/3/2014	6941	7620	7822	881	7460
S-17	6/3/2014	6740	6942	7110	370	6930
S-18	6/5/2014	7687	7352	7637	335	7560
S-19	6/5/2014	7147	7255	6725	530	7040
S-20	6/10/2014	6992	7351	7138	359	7160
S-21	6/10/2014	7265	7287	7459	194	7340
S-22	6/12/2014	7625	7130	7807	677	7520
S-23	6/12/2014	7900	7928	7661	267	7830
S-24	7/9/2014	7010	7484	7399	474	7300
S-25	7/9/2014	7703	7464	7555	229	7570

Appendix I

SR-RCP Batches 91-day Compressive Strength Data

TABLE I.1: TDOT Class D 91-Day Compressive Strength

ID #	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Cylinder 3 Result (psi)	Range (psi)	Compressive Strength (psi)
D-6	2/6/2014	6991	7287	7122	296	7130
D-7	2/6/2014	6603	6773	7012	409	6800
D-8	2/18/2014	6228	6534	6513	306	6430
D-9	2/18/2014	6338	6508	6553	215	6470
D-10	2/20/2014	6905	7093	6702	391	6900
D-11	2/20/2014	6858	6770	7166	396	6930
D-12	2/25/2014	6589	6908	6716	319	6740
D-13	2/25/2014	6728	6783	6982	254	6830
D-14	3/4/2014	6716	6733	6766	50	6740
D-15	3/4/2014	6191	6415	6453	224	6350
D-16	3/6/2014	6669	7188	7095	519	6980
D-17	3/6/2014	6578	7442	7279	864	7100
D-18	3/19/2014	6425	6771	6758	333	6650
D-19	3/19/2014	6792	6510	6540	282	6610
D-20	4/2/2014	7267	6913	7448	535	7210
D-21	4/2/2014	7266	7294	7448	182	7340
D-22	8/26/2014	5929	6158	6090	229	6060
D-23	8/26/2014	5991	6131	5814	317	5980
D-24	4/17/2014	6705	6656	6448	257	6600
D-25	4/17/2014	6225	6148	5997	228	6120

TABLE I.2: 50/35/15 91-Day Compressive Strength

ID #	Cast Date	Cylinder 1 Result (psi)	Cylinder 2 Result (psi)	Cylinder 3 Result (psi)	Range (psi)	Compressive Strength (psi)
S-6	5/16/2014	7147	7397	6915	482	7150
S-7	5/16/2014	7331	7362	6436	926	7040
S-8	5/20/2014	7324	6918	7416	498	7220
S-9	5/20/2014	7322	7396	7627	305	7450
S-10	5/23/2014	7155	7561	7524	406	7410
S-11	5/23/2014	7334	7378	7445	111	7390
S-12	7/23/2014	7862	8258	8133	396	8080
S-13	7/23/2014	7527	7943	7947	420	7810
S-14	7/11/2014	7368	7687	7291	396	7450
S-15	7/11/2014	7701	7788	7924	223	7800
S-16	6/3/2014	7561	7342	7984	642	7630
S-17	6/3/2014	7152	7024	7194	170	7120
S-18	6/5/2014	7924	7118	7557	806	7530
S-19	6/5/2014	7004	7250	7430	426	7230
S-20	6/10/2014	7320	7661	7624	341	7540
S-21	6/10/2014	7937	7326	8012	686	7760
S-22	6/12/2014	7861	7764	7843	97	7820
S-23	6/12/2014	8269	7738	8354	616	8120
S-24	7/9/2014	8019	7761	7606	413	7800
S-25	7/9/2014	7971	7823	7489	482	7760

Appendix J

28-Day Surface Resistivity Data

(immersion curing factor of 1.1 applied to final result)

TABLE J.1: TDOT Class D 28-Day SR

ID #	Cast Date	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
D-6	2/6/2014	13.5	13.7	12.9	0.8	14.7
D-7	2/6/2014	12.1	13.4	12.7	1.3	14.0
D-8	2/18/2014	12.8	13.2	13.3	0.5	14.4
D-9	2/18/2014	12.6	13.3	12.7	0.7	14.2
D-10	2/20/2014	12.4	12.6	12.2	0.4	13.6
D-11	2/20/2014	12.5	11.7	12.6	0.9	13.5
D-12	2/25/2014	12.8	13.3	13.2	0.5	14.4
D-13	2/25/2014	12.5	12.3	13.1	0.8	13.9
D-14	3/4/2014	12.4	11.8	12.8	1	13.6
D-15	3/4/2014	12.1	12.8	12.6	0.7	13.8
D-16	3/6/2014	12.6	12	11.8	0.8	13.3
D-17	3/6/2014	11	11.1	11.8	0.8	12.4
D-18	3/19/2014	12.7	12.3	12.6	0.4	13.8
D-19	3/19/2014	12.2	12.9	12.4	0.7	13.8
D-20	4/2/2014	12.5	12.3	12.6	0.3	13.7
D-21	4/2/2014	12.3	12.4	13	0.7	13.8
D-22	8/26/2014	12.2	12	12.1	0.2	13.3
D-23	8/26/2014	11.5	11.7	11.5	0.2	12.7
D-24	4/17/2014	13	12.5	13.6	1.1	14.3
D-25	4/17/2014	13.2	12.5	12.5	0.7	14.0

TABLE J.2: 50/35/15 28-Day SR

ID #	Cast Date	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
S-6	5/16/2014	28.9	28.5	26.9	2	30.9
S-7	5/16/2014	29.7	28	27.9	1.8	31.4
S-8	5/20/2014	31.6	29.2	31.5	2.4	33.8
S-9	5/20/2014	29.9	29.6	29.5	0.4	32.6
S-10	5/23/2014	28.7	28.4	28.9	0.5	31.5
S-11	5/23/2014	29.7	28.2	28.9	1.5	31.8
S-12	7/23/2014	29.9	30.6	29.1	1.5	32.9
S-13	7/23/2014	29.3	24.7	26.3	4.6	29.4
S-14	7/11/2014	26.7	26.3	26.1	0.6	29.0
S-15	7/11/2014	27.1	26.7	26.9	0.4	29.6
S-16	6/3/2014	28.7	30.4	28.5	1.9	32.1
S-17	6/3/2014	28.6	25.7	27.2	2.9	29.9
S-18	6/5/2014	29.6	31.1	30	1.5	33.3
S-19	6/5/2014	28.9	28.7	29.6	0.9	32.0
S-20	6/10/2014	30.9	30.4	29.5	1.4	33.3
S-21	6/10/2014	30.9	28	29.2	2.9	32.3
S-22	6/12/2014	28.9	28.1	27.4	1.5	30.9
S-23	6/12/2014	27.5	27.5	27.5	0	30.3
S-24	7/9/2014	30.2	29.8	29.8	0.4	32.9
S-25	7/9/2014	27.7	30	27.9	2.3	31.4

Appendix K

28-Day Accelerated Surface Resistivity Data

(immersion curing factor of 1.1 applied to final result)

TABLE K.1: TDOT Class D 28-Day Accelerated SR

ID #	Cast Date	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
D-6	2/6/2014	23.6	23.8	25.9	2.3	26.9
D-7	2/6/2014	24.7	23.6	25.5	1.9	27.1
D-8	2/18/2014	23.3	23	23.4	0.4	25.6
D-9	2/18/2014	23.2	22.7	23	0.5	25.3
D-10	2/20/2014	22.7	22.5	22.6	0.2	24.9
D-11	2/20/2014	21.9	21.9	23.3	1.4	24.6
D-12	2/25/2014	21.8	23.5	22.7	1.7	24.9
D-13	2/25/2014	23.9	22.9	22.9	1	25.6
D-14	3/4/2014	23.7	22.2	24.8	2.6	25.9
D-15	3/4/2014	23.5	21	23.8	2.8	25.0
D-16	3/6/2014	23.4	22.7	22.5	0.9	25.2
D-17	3/6/2014	23	23.1	22.9	0.2	25.3
D-18	3/19/2014	21.3	21.9	22.2	0.9	24.0
D-19	3/19/2014	20.9	22.2	22.4	1.5	24.0
D-20	4/2/2014	19.9	20.9	20.2	1	22.4
D-21	4/2/2014	21.5	20.5	21.4	1	23.2
D-22	8/26/2014	18.6	19.8	20.1	1.5	21.5
D-23	8/26/2014	19	20	19.8	1	21.6
D-24	4/17/2014	20.7	21.3	21.7	1	23.4
D-25	4/17/2014	21.1	22	21.6	0.9	23.7

TABLE K.2: 50/35/15 28-Day Accelerated SR

ID #	Cast Date	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
S-6	5/16/2014	37.6	38.8	40.5	2.9	42.9
S-7	5/16/2014	39.8	39.9	40.5	1.7	44.1
S-8	5/20/2014	44.3	41.9	41.1	3.2	46.7
S-9	5/20/2014	41.5	38.3	41.8	3.5	44.6
S-10	5/23/2014	38.6	37.3	38	1.3	41.8
S-11	5/23/2014	36.8	38.4	40.3	3.5	42.4
S-12	7/23/2014	38.5	38.4	37	1.5	41.8
S-13	7/23/2014	37.5	36.7	38.4	1.7	41.3
S-14	7/11/2014	39.4	39	37.6	1.8	42.5
S-15	7/11/2014	37.3	37.9	38.5	1.2	41.7
S-16	6/3/2014	40.4	38.2	38.9	2.2	43.1
S-17	6/3/2014	40.6	39.7	39.7	0.9	44.0
S-18	6/5/2014	36.6	36.3	37.4	1.1	40.4
S-19	6/5/2014	39.4	39.4	38.3	1.1	42.9
S-20	6/10/2014	35.3	35.9	36.7	1.4	39.6
S-21	6/10/2014	35.8	33.7	36.9	3.2	39.0
S-22	6/12/2014	35.8	38.5	37.2	2.7	40.9
S-23	6/12/2014	34.8	36.5	35.9	1.7	39.3
S-24	7/9/2014	34.2	36.1	35.2	1.9	38.7
S-25	7/9/2014	36.5	36.3	35.8	0.7	39.8

Appendix L

56-Day Surface Resistivity Data

(immersion curing factor of 1.1 applied to final result)

TABLE L.1: TDOT Class D 56-Day SR

ID #	Cast Date	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
D-6	2/6/2014	17.1	16.4	17.4	1	18.7
D-7	2/6/2014	15.8	16.9	15.7	1.2	17.7
D-8	2/18/2014	18.4	18.1	18.9	0.8	20.3
D-9	2/18/2014	16.7	17.9	17	1.2	18.9
D-10	2/20/2014	16.8	17.2	16.7	0.5	18.6
D-11	2/20/2014	16.7	16.5	16.6	0.2	18.3
D-12	2/25/2014	17.1	18.2	17.6	1.1	19.4
D-13	2/25/2014	16.9	16.7	17.2	0.5	18.6
D-14	3/4/2014	18	17	18.5	1.5	19.6
D-15	3/4/2014	18.2	20.5	19.1	2.3	21.2
D-16	3/6/2014	17.8	16.5	17	1.3	18.8
D-17	3/6/2014	15.5	16.2	16.1	0.7	17.5
D-18	3/19/2014	18.8	18	17.3	1.5	19.8
D-19	3/19/2014	17.9	18.2	18.4	0.5	20.0
D-20	4/2/2014	17	16.4	16.6	0.6	18.3
D-21	4/2/2014	16.4	16.7	17	0.4	18.4
D-22	8/26/2014	18	18	17.7	0.3	19.7
D-23	8/26/2014	17.9	17	17.7	0.9	19.3
D-24	4/17/2014	15.6	14.8	14.5	1.1	16.5
D-25	4/17/2014	15	14.7	15.8	1.1	16.7

TABLE L.2: 50/35/15 56-Day SR

ID #	Cast Date	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
S-6	5/16/2014	39.2	36.7	34.3	4.9	40.4
S-7	5/16/2014	37.4	36.6	37.4	0.8	40.8
S-8	5/20/2014	42.9	40.2	39.6	3.3	45.0
S-9	5/20/2014	40.2	40	39.9	0.3	44.0
S-10	5/23/2014	49.3	45.2	42.3	7	50.2
S-11	5/23/2014	46	42.3	44.4	3.7	48.7
S-12	7/23/2014	42.6	43.2	42.9	0.6	47.2
S-13	7/23/2014	40.3	39.1	40.2	1.2	43.9
S-14	7/11/2014	36.5	35.2	35.5	1.3	39.3
S-15	7/11/2014	36.5	35.4	35	1.5	39.2
S-16	6/3/2014	40	39.3	39.2	0.8	43.5
S-17	6/3/2014	35.2	36.5	36.4	1.3	39.6
S-18	6/5/2014	43.7	43	41.7	2	47.1
S-19	6/5/2014	41.2	38.8	41.3	2.5	44.5
S-20	6/10/2014	37.3	41.5	38.9	4.2	43.2
S-21	6/10/2014	39	35.9	40.7	4.8	42.4
S-22	6/12/2014	36.9	35.7	35.3	1.6	39.6
S-23	6/12/2014	34.9	35.2	33.9	1.3	38.1
S-24	7/9/2014	38.5	37.5	38.8	1.3	42.1
S-25	7/9/2014	37.8	36.4	38.5	2.1	41.3

Appendix M

91-Day Surface Resistivity Data

(immersion curing factor of 1.1 applied to final result)

TABLE M.1: TDOT Class D 91-Day SR

ID #	Cast Date	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
D-6	2/6/2014	26.3	23.5	25.7	2.8	27.7
D-7	2/6/2014	24.8	25.8	23.2	2.6	27.1
D-8	2/18/2014	23.1	24	23.1	0.9	25.7
D-9	2/18/2014	22	22.4	21.4	1	24.1
D-10	2/20/2014	24.5	24.5	23.8	0.7	26.7
D-11	2/20/2014	24.6	23.6	25.6	2	27.1
D-12	2/25/2014	26.5	25.3	23.7	2.8	27.7
D-13	2/25/2014	24	23.4	24.7	1.4	26.4
D-14	3/4/2014	22.5	23	22.4	0.6	24.9
D-15	3/4/2014	21.9	23.3	22.7	1.4	24.9
D-16	3/6/2014	23	22.6	21.6	1.4	24.6
D-17	3/6/2014	18.9	19.7	21.1	2.2	21.9
D-18	3/19/2014	23.5	22.4	21.9	1.6	24.9
D-19	3/19/2014	23	23.8	22.2	1.6	25.3
D-20	4/2/2014	23	22.6	21.9	1.1	24.8
D-21	4/2/2014	22.5	23.3	22.1	1.2	24.9
D-22	8/26/2014	23.4	24.3	21.9	2.4	25.5
D-23	8/26/2014	21.7	21.3	20.5	1.2	23.3
D-24	4/17/2014	23.9	25.9	24.7	2	27.3
D-25	4/17/2014	23.5	23.7	22.8	0.9	25.7

TABLE M.2: 50/35/15 91-Day SR

ID #	Cast Date	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
S-6	5/16/2014	44.2	41.8	40.9	3.3	46.5
S-7	5/16/2014	41.6	40.9	41.3	0.7	45.4
S-8	5/20/2014	51	45.9	50.2	5.1	53.9
S-9	5/20/2014	45.6	46.1	47.5	1.9	51.0
S-10	5/23/2014	45.7	46.7	46	1	50.7
S-11	5/23/2014	46.1	44.2	47.4	3.2	50.5
S-12	7/23/2014	59.2	58.3	59	0.9	64.7
S-13	7/23/2014	56.2	55.9	54.5	1.7	61.1
S-14	7/11/2014	46.8	45.7	46.1	1.3	50.8
S-15	7/11/2014	44.3	43.4	43.3	1	48.0
S-16	6/3/2014	45.8	43.4	44.9	2.4	49.2
S-17	6/3/2014	42.8	41.8	41.4	1.4	46.2
S-18	6/5/2014	45.7	46.2	48.6	2.9	51.5
S-19	6/5/2014	49.2	46.3	45.2	4	51.6
S-20	6/10/2014	46.3	47.5	47.8	1.5	51.9
S-21	6/10/2014	45.3	47.1	45.7	1.8	50.6
S-22	6/12/2014	43.4	41.6	42.1	1.8	46.6
S-23	6/12/2014	41.2	42	41.3	0.8	45.7
S-24	7/9/2014	50.9	49	51.6	2.6	55.6
S-25	7/9/2014	50.9	51.6	51.6	0.7	56.5

Appendix N

28-Day Accelerated Rapid Chloride Permeability Data

TABLE N.1: TDOT Class D 28-Day Accelerated RCP

ID #	Cast Date	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Slice 3 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
D-6	2/6/2014	1172	1102	1347	245	1210
D-7	2/6/2014	1158	1241	1141	100	1180
D-8	2/18/2014	1342	1431	1394	89	1390
D-9	2/18/2014	1508	1469	1356	152	1440
D-10	2/20/2014	1339	1356	1270	86	1320
D-11	2/20/2014	1416	1352	1304	112	1360
D-12	2/25/2014	1411	1418	1442	31	1420
D-13	2/25/2014	1463	1342	1421	121	1410
D-14	3/4/2014	1290	1231	1254	59	1260
D-15	3/4/2014	1294	1231	1495	264	1340
D-16	3/6/2014	1092	1034	1077	58	1070
D-17	3/6/2014	1104	1119	1096	23	1110
D-18	3/19/2014	1489	1308	1444	181	1410
D-19	3/19/2014	1394	1554	1476	160	1480
D-20	4/2/2014	1199	1244	1179	65	1210
D-21	4/2/2014	1069	1244	1089	165	1130
D-22	8/26/2014	1731	1467	1646	264	1620
D-23	8/26/2014	1432	1386	1635	255	1480
D-24	4/17/2014	1600	1229	1282	371	1370
D-25	4/17/2014	1316	1520	Malfunction	204	1420

TABLE N.2: 50/35/15 28-Day Accelerated RCP

ID #	Cast Date	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Slice 3 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
S-6	5/16/2014	573	590	549	41	570
S-7	5/16/2014	606	599	508	98	570
S-8	5/20/2014	571	596	587	25	590
S-9	5/20/2014	616	598	597	19	600
S-10	5/23/2014	628	657	587	70	620
S-11	5/23/2014	620	600	597	23	610
S-12	7/23/2014	627	632	608	24	620
S-13	7/23/2014	682	641	661	41	660
S-14	7/11/2014	600	604	647	47	620
S-15	7/11/2014	640	647	642	7	640
S-16	6/3/2014	631	591	588	43	600
S-17	6/3/2014	678	615	579	99	620
S-18	6/5/2014	625	599	642	43	620
S-19	6/5/2014	654	608	625	46	630
S-20	6/10/2014	635	639	666	31	650
S-21	6/10/2014	625	743	724	118	700
S-22	6/12/2014	642	647	626	21	640
S-23	6/12/2014	656	645	624	32	640
S-24	7/9/2014	637	738	663	101	680
S-25	7/9/2014	624	669	687	63	660

Appendix O

56-Day Rapid Chloride Permeability Data

TABLE O.1: TDOT Class D 56-Day RCP

ID #	Cast Date	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Slice 3 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
D-6	2/6/2014	2966	3019	3318	352	3100
D-7	2/6/2014	3121	3160	3149	39	3140
D-8	2/18/2014	2836	2677	3302	625	2940
D-9	2/18/2014	2943	3230	2863	367	3010
D-10	2/20/2014	2856	2652	2599	257	2700
D-11	2/20/2014	2608	2868	2798	260	2760
D-12	2/25/2014	2560	2361	2928	567	2620
D-13	2/25/2014	2650	2487	2770	283	2640
D-14	3/4/2014	2808	2717	2814	97	2780
D-15	3/4/2014	2699	2636	2677	63	2670
D-16	3/6/2014	2970	2776	2613	357	2790
D-17	3/6/2014	2903	2977	2722	255	2870
D-18	3/19/2014	2727	2551	2673	176	2650
D-19	3/19/2014	2629	2799	2636	170	2690
D-20	4/2/2014	2658	2732	2940	282	2780
D-21	4/2/2014	2720	2767	2781	61	2760
D-22	8/26/2014	3050	3076	3391	341	3170
D-23	8/26/2014	2687	2401	3067	666	2720
D-24	4/17/2014	2723	2566	3121	555	2800
D-25	4/17/2014	2713	2699	2683	30	2700

TABLE O.2: 50/35/15 56-Day RCP

ID #	Cast Date	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Slice 3 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
S-6	5/16/2014	871	812	865	59	850
S-7	5/16/2014	844	787	792	57	810
S-8	5/20/2014	867	828	901	73	870
S-9	5/20/2014	869	923	937	68	910
S-10	5/23/2014	864	835	833	31	840
S-11	5/23/2014	889	822	847	67	850
S-12	7/23/2014	902	876	895	26	890
S-13	7/23/2014	780	753	942	189	830
S-14	7/11/2014	860	821	899	78	860
S-15	7/11/2014	929	747	864	182	850
S-16	6/3/2014	850	839	810	40	830
S-17	6/3/2014	907	910	876	34	900
S-18	6/5/2014	983	947	850	133	930
S-19	6/5/2014	892	907	977	85	930
S-20	6/10/2014	934	932	896	38	920
S-21	6/10/2014	976	930	1019	89	980
S-22	6/12/2014	944	865	875	79	900
S-23	6/12/2014	870	993	981	123	950
S-24	7/9/2014	811	959	890	139	890
S-25	7/9/2014	936	875	901	61	900

Appendix P

91-Day Rapid Chloride Permeability Data

TABLE P.1: TDOT Class D 91-Day RCP

ID #	Cast Date	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Slice 3 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
D-6	2/6/2014	1791	1670	2024	354	1830
D-7	2/6/2014	1765	1865	1786	100	1810
D-8	2/18/2014	1591	1623	1647	56	1620
D-9	2/18/2014	1641	1727	1704	86	1690
D-10	2/20/2014	1804	1601	1628	203	1680
D-11	2/20/2014	1617	1782	1651	165	1680
D-12	2/25/2014	1662	1652	1578	84	1630
D-13	2/25/2014	1711	1722	1800	89	1740
D-14	3/4/2014	1623	1480	1597	143	1570
D-15	3/4/2014	1377	1629	Malfunction	252	1500
D-16	3/6/2014	1616	1441	1613	175	1560
D-17	3/6/2014	2002	1767	1885	235	1890
D-18	3/19/2014	1896	1783	1734	162	1800
D-19	3/19/2014	1876	1911	1738	173	1840
D-20	4/2/2014	1787	1666	1732	121	1730
D-21	4/2/2014	1588	1689	1707	119	1660
D-22	8/26/2014	2366	2440	2434	68	2410
D-23	8/26/2014	2204	2016	2312	296	2180
D-24	4/17/2014	1565	1669	1655	104	1630
D-25	4/17/2014	1806	1935	1677	258	1810

TABLE P.2: 50/35/15 91-Day RCP

ID #	Cast Date	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Slice 3 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
S-6	5/16/2014	701	741	685	56	710
S-7	5/16/2014	654	689	712	58	690
S-8	5/20/2014	653	611	714	103	660
S-9	5/20/2014	678	651	692	41	670
S-10	5/23/2014	739	704	657	82	700
S-11	5/23/2014	718	682	762	80	720
S-12	7/23/2014	668	593	588	80	620
S-13	7/23/2014	562	414	634	220	540
S-14	7/11/2014	572	529	561	43	550
S-15	7/11/2014	480	344	575	231	470
S-16	6/3/2014	689	680	655	35	680
S-17	6/3/2014	729	541	676	188	650
S-18	6/5/2014	716	762	678	84	720
S-19	6/5/2014	699	538	722	184	650
S-20	6/10/2014	665	722	668	57	690
S-21	6/10/2014	578	600	719	141	630
S-22	6/12/2014	736	684	791	107	740
S-23	6/12/2014	674	573	693	120	650
S-24	7/9/2014	714	638	764	126	710
S-25	7/9/2014	591	597	808	217	670

Appendix Q

Redo SR-RCP Rapid Chloride Permeability Data

TABLE Q.1: Redo RCP

ID #	Age	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Slice 3 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
D-22A	28-Day A	1446	1335	1424	111	1400
D-23A	28-Day A	1367	1731	1342	389	1480
D-22B	28-Day A	1746	1686	1694	100	1710
D-23B	28-Day A	16.3	1592	1759	167	1650
D-22A	91-Day	1719	1698	1863	165	1760
D-23A	91-Day	1794	1805	1741	64	1780
S-12A	56-Day	864	835	833	31	840
S-13A	56-Day	889	822	847	67	850
S-14A	56-Day	870	884	815	69	860
S-15A	56-Day	797	859	856	62	840
S-12A	91-Day	751	699	733	52	730
S-13A	91-Day	799	714	708	91	740
S-14A	91-Day	672	700	716	44	700
S-15A	91-Day	739	618	759	141	710

Appendix R

Redo SR-RCP Surface Resistivity Data

(immersion curing factor of 1.1 applied to final result)

TABLE R.1: Redo SR

ID #	Age	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
D-22A	28-Day A	22.2	20.9	21.3	1.3	23.6
D-23A	28-Day A	19.9	20.1	21.0	1.1	22.4
D-22B	28-Day A	18.1	19.3	19.1	1.2	20.7
D-23B	28-Day A	18.6	18.0	17.8	0.8	20.0
D-22A	91-Day	23.0	23.2	23.1	0.2	25.4
D-23A	91-Day	23.2	22.8	22.8	0.4	25.2
S-12A	56-Day	42.2	42.2	40.6	1.6	45.8
S-13A	56-Day	40.7	41.2	41.3	0.6	45.4
S-14A	56-Day	35.9	34.6	35.0	1.3	38.7
S-15A	56-Day	34.0	35.0	33.2	1.8	37.5
S-12A	91-Day	47.6	47.8	49.0	1.4	52.9
S-13A	91-Day	48.3	48.2	46.9	1.4	52.6
S-14A	91-Day	44.2	41.6	42.1	2.6	46.3
S-15A	91-Day	40.0	40.5	41.6	1.6	44.8

Appendix S

Unpublished TTU Class D 25% C Study Rapid Chloride Permeability Data

TABLE S.1: Unpublished TTU Class D 25% C Study RCP

ID #	Age (days)	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Slice 3 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
C-1	56	2753	2653	2435	318	2610
C-2	56	3236	3022	2984	252	3080
C-3	56	2749	2459	2239	510	2480
C-4	56	2852	2528	2545	324	2640
C-5	56	2141	2386	2891	750	2470
C-6	56	2820	2305	2749	515	2630
C-7	56	Power Outage				
C-8	56	Power Outage				
C-9	56	3072	2894	3001	178	2990
C-10	56	2821	2569	2982	413	2790
C-1	91	1438	1915	1757	477	1700
C-2	91	2068	1825	1929	243	1940
C-3	91	1756	1741	1880	139	1790
C-4	91	1808	1652	1686	156	1720
C-5	91	1917	1997	2054	137	1990
C-6	91	1364	1953	2544	1180	1950
C-7	91	1690	1933	1703	243	1780
C-8	91	2084	2111	1823	288	2010
C-9	91	2173	2055	2227	172	2150
C-10	91	2153	2130	2197	67	2160

Appendix T

Unpublished TTU Class D 25% C Study Surface Resistivity Data

(immersion curing factor of 1.1 applied to final result)

TABLE T.1: Unpublished TTU Class D 25% C Study SR

ID #	Age (days)	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
C-1	56	20.6	18.4	19.1	2.2	21.3
C-2	56	18.6	17.8	19.1	1.3	20.3
C-3	56	19.2	18.4	19.3	0.9	20.9
C-4	56	18.5	19.0	18.9	0.5	20.7
C-5	56	19.0	18.7	19.2	0.5	20.8
C-6	56	17.1	16.7	17.1	0.4	18.7
C-7	56	No RCP for Pair Due to Power Outage				
C-8	56	No RCP for Pair Due to Power Outage				
C-9	56	19.7	21.0	19.8	1.3	22.2
C-10	56	20.3	20.3	18.6	1.7	21.7
C-1	91	27.6	25.8	24.5	3.1	28.6
C-2	91	23.7	22.5	23.0	1.2	25.3
C-3	91	25.4	23.9	25.2	1.5	27.3
C-4	91	25.4	25.0	24.7	0.7	27.5
C-5	91	25.9	26.9	25.7	0.9	28.8
C-6	91	23.3	22.5	23.7	1.2	25.5
C-7	91	20.1	19.4	19.4	0.7	21.6
C-8	91	20.3	20.5	20.5	0.2	22.5
C-9	91	22.1	23.4	22.7	1.3	25.0
C-10	91	23.7	23.8	21.3	2.5	25.2

Appendix U

Unpublished TTU Slag-Fly Ash Study Rapid Chloride Permeability Data

TABLE U.1: Unpublished TTU Slag-Fly Ash Study RCP

Mixture / Batch #	Age (days)	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Slice 3 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
25F – 1	56	687	636	627	60	650
25F – 2	56	614	599	633	34	620
20F – 1	56	631	618	643	25	630
20F – 2	56	658	635	664	29	650
15F – 1	56	697	765	766	69	740
15F – 2	56	638	727	678	89	680
25C – 1	56	1056	1033	1048	23	1050
25C – 2	56	995	1055	1069	74	1040
20C – 1	56	1229	997	953	276	1060
20C – 2	56	1025	1002	964	61	1000
15C – 1	56	901	941	1010	109	950
15C – 2	56	915	968	898	70	930
25F – 1	91	490	445	462	45	470
25F – 2	91	423	453	446	23	440
20F – 1	91	482	465	481	17	480
20F – 2	91	522	486	523	37	510
15F – 1	91	564	562	569	7	570
15F – 2	91	622	589	576	46	600
25C – 1	91	844	788	773	71	800
25C – 2	91	875	799	Malfunction	76	840
20C – 1	91	818	1215	808	407	950
20C – 2	91	939	835	Malfunction	104	890
15C – 1	91	902	814	828	88	850
15C – 2	91	804	822	820	18	820

Appendix V

Unpublished TTU Slag-Fly Ash Study Surface Resistivity Data

(immersion curing factor of 1.1 applied to final result)

TABLE V.1: Unpublished TTU Slag-Fly Ash Study SR

Mixture / Batch #	Age (days)	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
25F – 1	56	52.5	50.2	58.3	8.1	59.0
25F – 2	56	49.6	52.0	53.5	3.9	56.9
20F – 1	56	47.1	47.4	47.3	0.3	52.0
20F – 2	56	48.1	48.5	47.6	0.9	52.8
15F – 1	56	51.5	50.0	50.5	1.5	52.6
15F – 2	56	51.5	50.0	50.7	1.5	55.7
25C – 1	56	39.7	41.4	40.1	1.7	44.4
25C – 2	56	39.2	40.6	38.8	1.8	43.5
20C – 1	56	35.6	36.9	36.9	1.3	40.1
20C – 2	56	35.6	35.3	37.3	2.0	39.7
15C – 1	56	45.9	47.1	43.4	3.7	50.0
15C – 2	56	42.8	43.5	41.6	1.9	46.9
25F – 1	91	61.5	60.7	62.5	1.8	67.7
25F – 2	91	56.2	59.1	63.5	7.3	65.6
20F – 1	91	55.2	56.6	54.6	2.0	61.0
20F – 2	91	55.6	55.4	55.2	0.4	60.9
15F – 1	91	63.8	60.8	60.4	3.4	67.8
15F – 2	91	58.2	63.4	62.8	5.2	67.6
25C – 1	91	49.4	50.5	49.7	1.1	54.9
25C – 2	91	49.6	49.1	47.6	2.0	53.7
20C – 1	91	38.5	39.5	39.9	1.4	43.3
20C – 2	91	38.7	39.5	40.0	1.3	43.3
15C – 1	91	48.4	51.3	48.9	2.9	54.5
15C – 2	91	53.9	54.3	52.9	1.4	59.0

Appendix W

Unpublished TTU Aggregate Study 56-Day Rapid Chloride Permeability Data

TABLE W.1: Unpublished TTU Aggregate Study 56-Day RCP

Mixture / Batch #	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Slice 3 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
80/20 Sand Variable - 1	1809	1938	1770	168	1840
80/20 Sand Variable - 2	1767	2422	1906	655	2030
80/20 LSCA1 – 1	2266	2590	2554	324	2470
80/20 LSCA1 - 2	2815	2167	2642	648	2540
80/20 GRCA1 – 1	5126	4654	4828	472	4870
80/20 GRCA1 - 2	4787	5528	4719	809	5010
80/20 GRCA2 – 1	4490	4270	4542	272	4430
80/20 GRCA2 - 2	4205	3364	4069	841	3880
80/20 LSCA2 – 1	1928	2641	2333	713	2300
80/20 LSCA2 - 2	2751	2869	2815	118	2810
80/20 LSCA3 – 1	2085	2427	2132	342	2220
80/20 LSCA3 - 2	2498	2460	2458	40	2470
80/20 LSCA4 – 1	2377	2589	2388	212	2450
80/20 LSCA4 - 2	2616	2675	2560	115	2620
80/20 LSCA5 – 1	2227	2547	2230	320	2340
80/20 LSCA5 - 2	2628	2570	2550	78	2580
100PC GRCA1 -1	3763	5129	3560	1569	4150
100PC GRCA1 - 2	3656	4946	3800	1290	4130
100PC GRCA1 - 3	4868	4544	3321	1547	4240
100PC GRCA2 - 1	3567	5706	4688	2139	4650
100PC GRCA2 - 2	5514	5470	3876	1638	4950
100PC GRCA2 - 3	Malfunction	5260	3768	1492	4520
100PC GRCA2 - 4	5644	5449	4356	1288	5150

Appendix X

Unpublished TTU Aggregate Study 56-Day Surface Resistivity Data

(immersion curing factor of 1.1 applied to final result)

TABLE X.1: Unpublished TTU Aggregate Study 56-Day SR

Mixture / Batch #	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
80/20 Sand Variable - 1	24.1	24.9	25.5	1.4	27.3
80/20 Sand Variable - 2	24.0	23.3	23.4	0.7	25.9
80/20 LSCA1 – 1	18.4	17.5	16.2	2.2	19.1
80/20 LSCA1 - 2	18.0	19.1	19.8	1.8	20.8
80/20 GRCA1 – 1	11.2	11.3	11.7	0.5	12.5
80/20 GRCA1 - 2	9.9	10.1	10.1	0.2	11.0
80/20 GRCA2 – 1	11.6	11.5	12.1	0.6	12.9
80/20 GRCA2 - 2	10.6	10.6	11.2	0.6	11.9
80/20 LSCA2 – 1	17.3	17.0	16.8	0.5	18.7
80/20 LSCA2 - 2	16.5	17.6	16.5	1.1	18.5
80/20 LSCA3 – 1	N/A	N/A	N/A	N/A	23.2
80/20 LSCA3 - 2	N/A	N/A	N/A	N/A	22.0
80/20 LSCA4 – 1	18.9	18.9	18.6	0.3	20.7
80/20 LSCA4 - 2	18.8	18.4	18.1	0.7	20.3
80/20 LSCA5 – 1	17.2	18.2	18.7	1.5	19.8
80/20 LSCA5 - 2	18.9	18.9	18.9	0	20.8
100PC GRCA1 -1	11.3	11.1	12.2	1.1	12.7
100PC GRCA1 - 2	9.9	10.0	10.1	0.2	11.1
100PC GRCA1 - 3	10.0	9.8	10.4	0.6	11.1
100PC GRCA2 - 1	8.5	8.5	8.6	0.1	9.4
100PC GRCA2 - 2	9.1	8.8	9.5	0.7	10.0
100PC GRCA2 - 3	9.7	9.7	9.9	0.2	10.8
100PC GRCA2 - 4	8.9	9.0	9.5	0.6	10.0

Appendix Y

Unpublished TTU Aggregate Study 28-Day Accelerated Rapid Chloride Permeability Data

TABLE Y.1: Unpublished TTU Aggregate Study 28-Day Accelerated RCP

Mixture / Batch #	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Slice 3 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
100PC GRCA1– 1	3866	4862	3594	1268	4110
100PC GRCA1 - 2	4717	3984	2900	1817	3870
100PC GRCA1 - 3	4336	3551	4536	985	4140

Appendix Z

Unpublished TTU Aggregate Study 28-Day Accelerated Surface Resistivity Data

(immersion curing factor of 1.1 applied to final result)

TABLE Z.1: Unpublished TTU Aggregate Study 28-Day Accelerated SR

Mixture / Batch #	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
100PC GRCA1– 1	8.2	8.1	9.0	0.9	9.3
100PC GRCA1 - 2	8.6	9.0	9.3	0.7	9.9
100PC GRCA1 - 3	8.8	8.6	8.9	0.3	9.6

Appendix AA

Unpublished Effect of SCM on SR Study 28-Day Surface Resistivity Data

(immersion curing factor of 1.1 applied to final result)

TABLE AA.1: Unpublished Effect of SCM on SR Study 28-Day SR

Mixture / Batch #	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
20F – 1	11.1	11.2	11.5	0.4	12.4
20F – 2	12.1	11.7	11.6	0.5	13.0
20F – 3	12.1	11.5	12.3	0.8	13.2
25F – 1	12.0	13.2	13.2	1.2	14.1
25F – 2	13.5	12.8	12.7	0.8	14.3
25F - 3	12.4	13.1	12.7	0.7	14.0
25C – 1	11.4	11.1	11.6	0.5	12.5
25C – 2	11.5	11.5	11.7	0.2	12.8
25C – 3	11.5	11.3	11.9	0.6	12.7
3.5SF20F - 1	25.0	25.0	24.9	0.1	27.5
3.5SF20F – 2	25.1	26.1	25.6	1.0	28.1
3.5SF20F – 3	25.8	26.2	25.4	0.8	28.4
5SF25C – 1	28.3	28.0	28.5	0.5	31.1
5SF25C – 2	27.5	27.1	28.0	0.9	30.3
5SF25C – 3	26.6	26.8	26.6	0.2	29.3
3.5MK20F - 1	28.1	28.4	27.8	0.6	30.9
3.5MK20F - 2	27.1	27.1	27.0	0.1	29.7
3.5MK20F – 3	26.1	27.1	26.7	1.0	29.3
5MK25C – 1	29.9	30.5	29.9	0.6	33.1
5MK25C – 2	30.2	30.2	29.9	0.3	33.1
5MK25C - 3	29.7	29.6	30.2	0.6	32.8

TABLE AA.2: Unpublished Effect of SCM on SR Study 28-Day SR Continued

Mixture / Batch #	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
45SL – 1	27.1	26.8	27.7	0.9	29.9
45SL – 2	28.4	27.4	28.5	1.1	30.9
45SL – 3	29.0	30.0	30.2	1.2	32.7
35SL15F – 1	29.3	28.4	28.9	0.9	31.8
35SL15F – 2	28.7	29.2	28.9	0.5	31.8
35SL15F – 3	27.5	27.6	28.5	1.0	30.6
100PC – 1	11.0	11.6	11.0	0.6	12.3
100PC – 2	10.7	10.4	10.4	0.3	11.5
100PC - 3	11.0	10.9	10.9	0.1	12.0
45SL5MK – 1	90.8	94.1	91.7	3.3	101.4
45SL5MK – 2	91.4	89.7	93.1	3.4	100.5
45SL5MK – 3	89.5	93.9	92.4	4.4	101.1
35SL15MK – 1	128.7	125.3	127.0	3.4	139.7
35SL15MK – 2	126.0	126.8	123.2	3.6	137.9
35SL15MK – 3	126.9	127.9	126.4	1.5	139.7
50C – 1	11.8	12.2	11.8	0.4	13.1
50C – 2	12.1	11.7	11.6	0.5	13.0
50C - 3	11.6	11.7	11.1	0.6	12.6

Appendix AB

Unpublished Effect of SCM on SR Study 56-day Surface Resistivity Data

(immersion curing factor of 1.1 applied to final result)

TABLE AB.1: Unpublished Effect of SCM on SR Study 56-Day SR

Mixture / Batch #	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
20F – 1	16.0	16.1	16.3	0.3	17.7
20F – 2	16.9	16.4	16.0	0.9	18.1
20F – 3	16.5	15.8	16.6	0.8	17.9
25F – 1	19.5	20.5	20.3	1.0	22.1
25F – 2	20.9	20.2	20.2	0.7	22.5
25F - 3	19.8	20.3	20.1	0.5	22.1
25C – 1	16.2	15.8	16.5	0.7	17.8
25C – 2	16.1	16.6	17.0	0.9	18.2
25C – 3	16.1	16.1	16.9	0.8	18.0
3.5SF20F - 1	39.5	39.0	39.6	0.6	43.3
3.5SF20F – 2	39.8	41.2	41.2	1.4	44.8
3.5SF20F – 3	41.0	41.2	40.5	0.7	45.0
5SF25C – 1	50.1	46.7	48.2	3.4	53.2
5SF25C – 2	45.5	44.9	46.9	2.0	50.3
5SF25C – 3	44.5	44.3	45.2	0.9	49.1
3.5MK20F - 1	37.5	36.8	35.3	2.2	40.1
3.5MK20F - 2	34.5	34.1	34.3	0.4	37.7
3.5MK20F – 3	32.7	35.2	33.8	2.5	37.3
5MK25C – 1	39.3	37.3	36.5	2.8	41.5
5MK25C – 2	37.4	37.6	36.9	0.7	41.0
5MK25C - 3	37.1	36.3	37.3	1.0	40.6

TABLE AB.2: Unpublished Effect of SCM on SR Study 56-Day SR Continued

Mixture / Batch #	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
45SL – 1	32.8	32.5	32.6	0.3	35.9
45SL – 2	34.1	32.7	33.7	1.4	36.9
45SL – 3	34.7	34.7	34.4	0.3	38.0
35SL15F – 1	42.4	39.9	41.1	2.5	45.2
35SL15F – 2	40.1	41.7	41.3	1.6	45.1
35SL15F – 3	39.8	39.5	40.9	1.4	44.1
100PC – 1	13.2	13.8	12.8	1.0	14.6
100PC – 2	12.3	12.0	12.1	0.3	13.3
100PC - 3	12.9	12.5	12.7	0.4	14.0
45SL5MK – 1	102.8	105.5	103.1	2.7	114.2
45SL5MK – 2	102.9	101.6	107.0	5.4	114.2
45SL5MK – 3	104.1	107.2	104.6	3.1	115.8
35SL15MK – 1	158.4	155.5	155.7	2.9	172.2
35SL15MK – 2	155.5	163.2	152.2	11.0	172.7
35SL15MK – 3	162.5	161.9	160.0	2.5	177.6
50C – 1	20.2	21.0	20.5	0.8	22.6
50C – 2	20.3	19.5	19.6	0.8	21.8
50C - 3	19.8	19.7	18.9	0.9	21.4

Appendix AC

Unpublished Effect of SCM on SR Study 91-Day Surface Resistivity Data

(immersion curing factor of 1.1 applied to final result)

TABLE AC.1: Unpublished Effect of SCM on SR Study 91-Day SR

Mixture / Batch #	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
20F – 1	26.7	26.6	26.3	0.4	29.2
20F – 2	28.0	26.3	25.7	2.3	29.3
20F – 3	26..2	25.3	26.1	0.9	28.5
25F – 1	32.1	32.6	33.4	1.3	36.0
25F – 2	32.7	31.6	31.0	1.7	34.9
25F - 3	31.4	31.8	32.0	0.6	34.9
25C – 1	25.6	25.1	25.4	0.5	27.9
25C – 2	25.3	25.8	26.1	0.8	28.3
25C – 3	25.0	25.2	26.1	1.1	28.0
3.5SF20F - 1	53.5	52.6	52.4	1.1	58.1
3.5SF20F – 2	52.7	54.6	54.4	1.9	59.3
3.5SF20F – 3	54.5	54.8	53.6	1.2	59.7
5SF25C – 1	64.8	62.1	65.3	3.2	70.5
5SF25C – 2	60.4	58.5	61.3	2.8	66.1
5SF25C – 3	58.3	59.1	58.3	0.8	64.4
3.5MK20F - 1	47.3	46.1	45.9	1.4	51.0
3.5MK20F - 2	45.2	44.5	44.3	0.9	49.1
3.5MK20F – 3	42.0	44.3	42.5	2.3	47.2
5MK25C – 1	48.4	44.8	45.0	3.6	50.7
5MK25C – 2	45.0	44.3	44.7	0.7	49.1
5MK25C - 3	44.5	43.1	44.9	1.8	48.6

TABLE AC.2: Unpublished Effect of SCM on SR Study 91-Day SR Continued

Mixture / Batch #	Cylinder 1 Result (kilohm-cm)	Cylinder 2 Result (kilohm-cm)	Cylinder 3 Result (kilohm-cm)	Range (kilohm-cm)	Surface Resistivity (kilohm-cm)
45SL – 1	41.3	39.1	40.0	2.2	44.1
45SL – 2	42.0	40.0	41.5	2.0	45.3
45SL – 3	43.1	43.6	43.9	0.8	47.9
35SL15F – 1	49.7	49.4	50.9	1.5	55.0
35SL15F – 2	49.6	51.0	49.5	1.5	55.0
35SL15F – 3	48.3	47.4	49.6	2.2	53.3
100PC – 1	15.9	16.7	15.9	0.8	17.8
100PC – 2	15.2	14.6	14.6	0..6	16.3
100PC - 3	15.4	15.1	15.2	0.3	16.7
45SL5MK – 1	113.8	117.0	117.7	3.9	127.8
45SL5MK – 2	112.5	111.2	115.6	4.4	124.4
45SL5MK – 3	112.4	116.3	113.7	3.9	125.5
35SL15MK – 1	184.3	176.5	175.9	8.4	196.8
35SL15MK – 2	177.8	180.6	179.7	2.8	197.3
35SL15MK – 3	187.3	186.5	186.1	1.2	205.3
50C – 1	31.3	31.7	30.6	1.1	34.3
50C – 2	29.6	28.1	28.4	1.5	31.5
50C - 3	28.6	28.7	28.9	0.3	31.6

Appendix AD

RES 2010-007 TDOT Class D 56-Day Rapid Chloride Permeability

TABLE AD.1: RES 2010-007 TDOT Class D 56-Day RCP

Identification	Cast Date	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
A-1	6/24/2010	Leak	1215		1220
A-2	6/29/2010	1339	1605	266	1470
A-3	6/29/2010	1661	1670	9	1670
A-4	6/29/2010	Leak	1428		1430
A-5	6/29/2010	1640	1568	72	1600
A-6	7/15/2010	1459	1484	25	1470
A-7	7/15/2010	1365	1495	130	1430
A-8	7/15/2010	1777	1749	28	1760
A-9	7/21/2010	1457	1676	219	1570
A-10	7/21/2010	1673	1566	107	1620
B-1	6/22/2010	1602	1559	43	1580
B-2	6/22/2010	972	693	279	830
B-3	6/22/2010	1893	Leak		1890
B-4	6/24/2010	893	1605	712	1250
B-5	6/24/2010	1748	1591	157	1670
B-6	7/29/2010	1818	1591	227	1700
B-7	7/29/2010	1496	1613	117	1550
B-8	8/5/2010	1330	1483	153	1410
B-9	8/5/2010	1389	1482	93	1440
B-10	8/5/2010	1404	1588	184	1500
C-1	6/22/2010	1703	1654	49	1680
C-2	6/24/2010	1538	1718	180	1630
C-3	7/13/2010	1493	1510	17	1500
C-4	7/13/2010	1552	1482	70	1520
C-5	7/13/2010	Leak	1428		1430
C-6	7/13/2010	1473	1378	95	1430
C-7	7/21/2010	1662	1567	95	1610
C-8	7/21/2010	1825	1620	205	1720
C-9	7/29/2010	1639	1755	116	1700
C-10	7/29/2010	1982	1591	391	1790

TABLE AD.2: RES 2010-007 TDOT Class D 56-Day RCP Continued

Identification	Cast Date	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
D-1	7/1/2010	1760	1566	194	1660
D-2	7/1/2010	1629	1677	48	1650
D-3	7/6/2010	1392	1482	90	1440
D-4	7/8/2010	1609	1719	110	1660
D-5	7/27/2010	1513	1651	138	1580
D-6	8/3/2010	1410	1544	134	1480
D-7	8/3/2010	1618	1718	100	1670
D-8	8/3/2010	1611	1552	59	1580
D-9	7/1/2010	1810	1358	452	1580
D-10	7/6/2010	1803	1541	262	1670
E-1	7/1/2010	1608	Leak		1610
E-2	7/6/2010	1589	1550	39	1570
E-3	7/6/2010	Leak	1407		1410
E-4	7/8/2010	1312	Leak		1310
E-5	7/8/2010	1538	1588	50	1560
E-6	7/8/2010	1384	1414	30	1400
E-7	7/27/2010	1515	1434	81	1470
E-8	7/27/2010	1580	1512	68	1550
E-9	7/27/2010	1679	1387	292	1530
E-10	8/3/2010	1392	1301	91	1350

Appendix AE

RES 2011-09 TDOT Class D 56-Day Rapid Chloride Permeability

TABLE AE.1: RES 2011-09 TDOT Class D 56-Day RCP

Identification	**Slice 1 Result (Coulombs)**	**Slice 2 Result (Coulombs)**	**Slice 3 Result (Coulombs)**	**Range (Coulombs)**	**Rapid Chloride Permeability (Coulombs)**
SL-1	665	795	801	136	750
SL-2	847	827	807	40	830
SL-3	811	724	698	113	740
SL-4	764	843	617	226	740
SL-5	1007	617	890	390	840
SL-6	970	920	935	50	940
SL-7	789	754	727	62	760
SL-8	927	786	845	141	850
SL-9	714	900	965	251	860
SL-10	840	875	744	131	820
SF-1	812	807	806	6	810
SF-2	679	805	830	151	770
SF-3	913	805	753	160	820*
SF-4	774	861	880	106	840*
SF-5	731	Malfunction	648	83	690
SF-6	594	813	770	319	730
SF-7	865	826	763	102	820
SF-8	841	676	824	165	780
SF-9	783	808	738	70	780
SF-10	946	665	915	281	840
MK-1	709	612	573	136	630
MK-2	725	639	730	91	700
MK-3	813	789	764	49	790
MK-4	849	679	816	170	780
MK-5	710	726	763	53	730
MK-6	822	Malfunction	819	3	820
MK-7	781	808	725	83	770
MK-8	873	529	799	74	730
MK-9	718	736	667	69	710
MK-10	731	Malfunction	828	97	780

* - test ran 9 hours instead of 6 due to operator error

Appendix AF

RES 2013-11 TDOT Class D 56-Day Rapid Chloride Permeability

TABLE AF.1: RES 2013-11 TDOT Class D 56-Day RCP

Identification	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Slice 3 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
CSF-1	539	567	559	28	560
CSF-2	425	486	426	61	450
CSF-3	509	520	501	19	510
CSF-4	348	439	496	148	430
CSF-5	463	480	477	17	470
CSF-6	507	510	449	61	490
CSF-7	Malfunction	488	560	72	520
CSF-8	438	590	500	152	510
CSF-9	681	658	638	43	660
CSF-10	477	548	458	90	490
CSF-11	627	628	678	51	640
CMK-1	745	723	763	40	740
CMK-2	782	749	737	45	760
CMK-3	803	781	787	22	790
CMK-4	698	781	764	83	750
CMK-5	749	770	730	40	750
CMK-6	693	739	744	51	730
CMK-7	800	767	702	98	760
CMK-8	788	777	825	48	800
CMK-9	762	761	759	3	760
CMK-10	788	809	784	25	790
CMK-11	810	790	Malfunction	20	800

TABLE AF.2: RES 2013-11 TDOT Class D 56-Day RCP Continued

Identification	Slice 1 Result (Coulombs)	Slice 2 Result (Coulombs)	Slice 3 Result (Coulombs)	Range (Coulombs)	Rapid Chloride Permeability (Coulombs)
50/35/15-1	802	761	778	41	780
50/35/15-2	759	757	755	4	760
50/35/15-3	772	764	814	50	780
50/35/15-4	780	811	813	33	800
50/35/15-5	875	799	837	76	840
50/35/15-6	798	863	839	65	830
50/35/15-7	662	Malfunction	712	50	690
50/35/15-8	699	749	775	76	740
50/35/15-9	725	746	761	36	740
50/35/15-10	804	806	810	6	810
50/35/15-11	763	817	852	89	810
62/35/3-1	893	883	874	19	880
62/35/3-2	808	807	829	22	820
62/35/3-3	839	856	793	63	830
62/35/3-4	830	861	835	31	840
62/35/3-5	967	922	879	88	920
62/35/3-6	973	970	947	26	960
62/35/3-7	944	982	888	94	940
62/35/3-8	979	904	1027	123	970
62/35/3-9	875	837	902	65	870
62/35/3-10	919	962	943	43	940
62/35/3-11	934	895	944	49	920

Appendix AG

RES 2010-035 TDOT Class D 91-Day Rapid Chloride Permeability

TABLE AG.1: RES 2010-035 TDOT Class D 91-Day RCP

Identification	Slice 1 (coulombs)	Slice 2 (coulombs)	Range (coulombs)	Result (coulombs)
D-1	1198	1224	26	1210
D-2	1212	1126	86	1170
D-3	1273	1126	147	1200
D-4	1345	1235	110	1290
D-5	1231	Leak		1230
D-6	1286	1143	143	1210
D-7	1088	Leak		1090
D-8	1407	1177	230	1290
D-9	1326	1169	157	1250
D-10	1276	1235	41	1260

Appendix AH

TDOT Class D Rapid Chloride Permeability Predicted and Measured Results

TABLE AH.1: TDOT Class D RCP Predicted and Measured Results

ID #	Measured 28-Day Accelerated RCP (Coulombs)	56-Day RCP Predicted by Equation (Coulombs)	Measured 56-Day RCP (Coulombs)	91-Day RCP Predicted by Equation with 28-Day Data (Coulombs)	91-Day RCP Predicted by Equation with 56-Day Data (Coulombs)	Measured 91-Day RCP (Coulombs)
D-6	1210	2396	3100	1534	1903	1830
D-7	1180	2309	3140	1486	1924	1810
D-8	1390	2939	2940	1829	1819	1620
D-9	1440	3096	3010	1913	1855	1690
D-10	1320	2723	2700	1713	1691	1680
D-11	1360	2846	2760	1779	1723	1680
D-12	1420	3033	2620	1879	1649	1630
D-13	1410	3001	2640	1862	1659	1740
D-14	1260	2543	2780	1615	1734	1570
D-15	1340	2784	2670	1746	1675	1500
D-16	1070	1998	2790	1312	1739	1560
D-17	1110	2110	2870	1375	1782	1890
D-18	1410	3001	2650	1862	1665	1800
D-19	1480	3224	2690	1980	1686	1840
D-20	1210	2396	2780	1534	1734	1730
D-21	1130	2166	2760	1406	1723	1660
D-22	1620	3683	3170	2221	1939	2410
D-23	1480	3224	2720	1980	1702	2180
D-24	1370	2877	2800	1795	1745	1630
D-25	1420	3033	2700	1879	1691	1810

Appendix AI

50/35/15 Rapid Chloride Permeability Predicted and Measured Results

TABLE AI.1: 50/35/15 RCP Predicted and Measured Results

ID #	Measured 28-Day Accelerated RCP (Coulombs)	56-Day RCP Predicted by Equation (Coulombs)	Measured 56-Day RCP (Coulombs)	91-Day RCP Predicted by Equation with 28-Day Data (Coulombs)	91-Day RCP Predicted by Equation with 56-Day Data (Coulombs)	Measured 91-Day RCP (Coulombs)
S-6	570	790	850	590	632	710
S-7	570	790	810	590	607	690
S-8	590	831	870	617	645	660
S-9	600	852	910	630	670	670
S-10	620	894	840	657	626	700
S-11	610	873	850	643	632	720
S-12	620	894	890	657	657	620
S-13	660	980	830	711	619	540
S-14	620	894	860	657	638	550
S-15	640	937	850	684	632	470
S-16	600	852	830	630	619	680
S-17	620	894	900	657	664	650
S-18	620	894	930	657	682	720
S-19	630	915	930	670	682	650
S-20	650	959	920	697	676	690
S-21	700	1069	980	766	713	630
S-22	640	937	900	684	664	740
S-23	640	937	950	684	695	650
S-24	680	1025	890	738	657	710
S-25	660	980	900	711	664	670

Appendix AJ

Rapid Chloride Permeability Predicted (with equation based on additional results) and Measured Results

TABLE AJ.1: TDOT Class D RCP Predicted and Measured Results with Additional Results

ID #	Measured 56-Day RCP (Coulombs)	91-Day RCP Predicted by Equation with 56-Day Data (Coulombs)	Measured 91-Day RCP (Coulombs)
D-6	3100	2027	1830
D-7	3140	2050	1810
D-8	2940	1937	1620
D-9	3010	1976	1690
D-10	2700	1800	1680
D-11	2760	1834	1680
D-12	2620	1754	1630
D-13	2640	1765	1740
D-14	2780	1846	1570
D-15	2670	1782	1500
D-16	2790	1851	1560
D-17	2870	1897	1890
D-18	2650	1771	1800
D-19	2690	1794	1840
D-20	2780	1846	1730
D-21	2760	1834	1660
D-22	3170	2067	2410
D-23	2720	1811	2180
D-24	2800	1857	1630
D-25	2700	1800	1810

TABLE AJ.2: 50/35/15 RCP Predicted and Measured Results with Additional Results

ID #	Measured 56-Day RCP (Coulombs)	91-Day RCP Predicted by Equation with 56-Day Data (Coulombs)	Measured 91-Day RCP (Coulombs)
S-6	850	665	710
S-7	810	638	690
S-8	870	678	660
S-9	910	705	670
S-10	840	658	700
S-11	850	665	720
S-12	890	691	620
S-13	830	651	540
S-14	860	671	550
S-15	850	665	470
S-16	830	651	680
S-17	900	698	650
S-18	930	718	720
S-19	930	718	650
S-20	920	711	690
S-21	980	751	630
S-22	900	698	740
S-23	950	731	650
S-24	890	691	710
S-25	900	698	670

TABLE AJ.3: Additional RCP Predicted and Measured Results with Additional Results

ID #	Measured 56-Day RCP (Coulombs)	91-Day RCP Predicted by Equation with 56-Day Data (Coulombs)	Measured 91-Day RCP (Coulombs)
50/25/25F-1	650	527	470
50/25/25F-2	620	506	440
50/30/20F-1	630	513	480
50/30/20F-2	650	527	510
50/35/15F-1	740	590	570
50/35/15F-2	680	548	600
50/25/25C-1	1050	797	800
50/25/25C-2	1040	791	840
50/30/20C-1	1060	804	950
50/30/20C-2	1000	764	890
50/35/15C-1	950	731	850
50/35/15C-2	930	718	820
D75PC25C-1	2610	1748	1700
D75PC25C-2	3080	2016	1940
D75PC25C-3	2480	1673	1790
D75PC25C-4	2640	1765	1720
D75PC25C-5	2470	1667	1990
D75PC25C-6	2630	1759	1950
D75PC25C-7	2990	1965	2150
D75PC25C-8	2790	1851	2160

Appendix AK

TDOT Class D Surface Resistivity Predicted and Measured Results

TABLE AK.1: TDOT Class D SR Predicted and Measured Results

ID #	Measured 28-Day SR (kilohm-cm)	56-Day SR Predicted by 28-Day SR Equation (kilohm-cm)	Measured 56-Day SR (kilohm-cm)	91-Day SR Predicted by 28-Day SR Equation (kilohm-cm)	91-Day SR Predicted by 56-Day SR Equation (kilohm-cm)	Measured 91-Day SR (kilohm-cm)
D-6	14.7	20.1	18.7	27.1	25.7	27.7
D-7	14.0	19.2	17.7	26.1	24.6	27.1
D-8	14.4	19.7	20.3	26.7	27.5	25.7
D-9	14.2	19.4	18.9	26.3	26.0	24.1
D-10	13.6	18.7	18.6	25.5	25.6	26.7
D-11	13.5	18.5	18.3	25.3	25.2	27.1
D-12	14.4	19.7	19.4	26.7	26.5	27.7
D-13	13.9	19.0	18.6	25.9	25.6	26.4
D-14	13.6	18.6	19.6	25.4	26.7	24.9
D-15	13.8	18.8	21.2	25.7	28.5	24.9
D-16	13.3	18.3	18.8	25.0	25.8	24.6
D-17	12.4	17.0	17.5	23.6	24.4	21.9
D-18	13.8	18.9	19.8	25.7	27.0	24.9
D-19	13.8	18.8	20.0	25.7	27.2	25.3
D-20	13.7	18.8	18.3	25.6	25.3	24.8
D-21	13.8	18.9	18.4	25.8	25.3	24.9
D-22	13.3	18.2	19.7	25.0	26.8	25.5
D-23	12.7	17.4	19.3	24.0	26.4	23.3
D-24	14.3	19.6	16.5	26.6	23.2	27.3
D-25	14.0	19.2	16.7	26.1	23.4	25.7

TABLE AK.2: TDOT Class D SR Predicted and Measured Results Continued

ID #	Measured 28-Day Accelerated SR (kilohm-cm)	56-Day SR Predicted by 28-Day Accelerated SR Equation (kilohm-cm)	Measured 56-Day SR (kilohm-cm)	91-Day SR Predicted by 28-Day Accelerated SR Equation (kilohm-cm)	Measured 91-Day SR (kilohm-cm)
D-6	26.9	22.0	18.7	29.2	27.7
D-7	27.1	22.2	17.7	29.5	27.1
D-8	25.6	20.4	20.3	27.4	25.7
D-9	25.3	20.0	18.9	27.1	24.1
D-10	24.9	19.6	18.6	26.5	26.7
D-11	24.6	19.3	18.3	26.2	27.1
D-12	24.9	19.6	19.4	26.6	27.7
D-13	25.6	20.4	18.6	27.4	26.4
D-14	25.9	20.8	19.6	27.9	24.9
D-15	25.0	19.8	21.2	26.8	24.9
D-16	25.2	19.9	18.8	26.9	24.6
D-17	25.3	20.1	17.5	27.1	21.9
D-18	24.0	18.5	19.8	25.4	24.9
D-19	24.0	18.6	20.0	25.4	25.3
D-20	22.4	16.7	18.3	23.3	24.8
D-21	23.2	17.7	18.4	24.4	24.9
D-22	21.5	15.8	19.7	22.2	25.5
D-23	21.6	15.9	19.3	22.3	23.3
D-24	23.4	17.8	16.5	24.5	27.3
D-25	23.7	18.3	16.7	25.0	25.7

Appendix AL

50/35/15 Surface Resistivity Predicted and Measured Results

TABLE AL.1: 50/35/15 SR Predicted and Measured Results

ID #	Measured 28-Day SR (kilohm-cm)	56-Day SR Predicted by 28-Day SR Equation (kilohm-cm)	Measured 56-Day SR (kilohm-cm)	91-Day SR Predicted by 28-Day SR Equation (kilohm-cm)	91-Day SR Predicted by 56-Day SR Equation (kilohm-cm)	Measured 91-Day SR (kilohm-cm)
S-6	30.9	41.9	40.4	50.3	48.4	46.5
S-7	31.4	42.6	40.8	50.9	48.9	45.4
S-8	33.8	45.9	45.0	54.2	52.9	53.9
S-9	32.6	44.3	44.0	52.6	52.0	51.0
S-10	31.5	42.8	50.2	51.1	57.9	50.7
S-11	31.8	43.2	48.7	51.5	56.4	50.5
S-12	32.9	44.6	47.2	52.9	55.0	64.7
S-13	29.4	40.0	43.9	48.3	51.9	61.1
S-14	29.0	39.4	39.3	47.7	47.3	50.8
S-15	29.6	40.2	39.2	48.5	47.2	48.0
S-16	32.1	43.6	43.5	51.9	51.4	49.2
S-17	29.9	40.6	39.6	48.9	47.7	46.2
S-18	33.3	45.1	47.1	53.5	54.9	51.5
S-19	32.0	43.4	44.5	51.7	52.4	51.6
S-20	33.3	45.1	43.2	53.5	51.1	51.9
S-21	32.3	43.8	42.4	52.2	50.4	50.6
S-22	30.9	42.0	39.6	50.4	47.6	46.6
S-23	30.3	41.1	38.1	49.4	46.2	45.7
S-24	32.9	44.7	42.1	53.0	50.1	55.6
S-25	31.4	42.6	41.3	50.9	49.3	56.5

TABLE AL.2: 50/35/15 SR Predicted and Measured Results Continued

ID #	Measured 28-Day Accelerated SR (kilohm-cm)	56-Day SR Predicted by 28-Day Accelerated SR Equation (kilohm-cm)	Measured 56-Day SR (kilohm-cm)	91-Day SR Predicted by 28-Day Accelerated SR Equation (kilohm-cm)	Measured 91-Day SR (kilohm-cm)
S-6	42.9	43.8	40.4	48.4	46.5
S-7	44.1	45.6	40.8	48.9	45.4
S-8	46.7	49.7	45.0	52.9	53.9
S-9	44.6	46.4	44.0	52.0	51.0
S-10	41.8	42.1	50.2	57.9	50.7
S-11	42.4	43.0	48.7	56.4	50.5
S-12	41.8	42.1	47.2	55.0	64.7
S-13	41.3	41.4	43.9	51.9	61.1
S-14	42.5	43.3	39.3	47.3	50.8
S-15	41.7	42.0	39.2	47.2	48.0
S-16	43.1	44.1	43.5	51.4	49.2
S-17	44.0	45.5	39.6	47.7	46.2
S-18	40.4	40.2	47.1	54.9	51.5
S-19	42.9	43.9	44.5	52.4	51.6
S-20	39.6	38.9	43.2	51.1	51.9
S-21	39.0	38.1	42.4	50.4	50.6
S-22	40.9	40.8	39.6	47.6	46.6
S-23	39.3	38.5	38.1	46.2	45.7
S-24	38.7	37.6	42.1	50.1	55.6
S-25	39.8	39.3	41.3	49.3	56.5

Appendix AM

Surface Resistivity Predicted (with equation based on additional results) and Measured Results

TABLE AM.1: TDOT Class D SR Predicted and Measured Results with Additional Results

ID #	Measured 28-Day SR (kilohm-cm)	56-Day SR Predicted by 28-Day SR Equation (kilohm-cm)	Measured 56-Day SR (kilohm-cm)	91-Day SR Predicted by 28-Day SR Equation (kilohm-cm)	91-Day SR Predicted by 56-Day SR Equation (kilohm-cm)	Measured 91-Day SR (kilohm-cm)
D-6	14.7	21.7	18.7	29.6	26.1	27.7
D-7	14.0	20.8	17.7	28.7	25.0	27.1
D-8	14.4	21.3	20.3	29.3	27.9	25.7
D-9	14.2	21.1	18.9	29.0	26.3	24.1
D-10	13.6	20.3	18.6	28.2	26.0	26.7
D-11	13.5	20.2	18.3	28.1	25.7	27.1
D-12	14.4	21.3	19.4	29.3	26.9	27.7
D-13	13.9	20.7	18.6	28.6	26.0	26.4
D-14	13.6	20.3	19.6	28.2	27.1	24.9
D-15	13.8	20.6	21.2	28.5	28.9	24.9
D-16	13.3	20.0	18.8	27.8	26.2	24.6
D-17	12.4	18.9	17.5	26.7	24.8	21.9
D-18	13.8	20.6	19.8	28.5	27.3	24.9
D-19	13.8	20.6	20.0	28.5	27.5	25.3
D-20	13.7	20.5	18.3	28.3	25.7	24.8
D-21	13.8	20.6	18.4	28.5	25.8	24.9
D-22	13.3	20.0	19.7	27.8	27.2	25.5
D-23	12.7	19.3	19.3	27.0	26.8	23.3
D-24	14.3	21.2	16.5	29.1	23.7	27.3
D-25	14.0	20.8	16.7	28.7	23.9	25.7

TABLE AM.2: 50/35/15 SR Predicted and Measured Results with Additional Results

ID #	Measured 28-Day SR (kilohm-cm)	56-Day SR Predicted by 28-Day SR Equation (kilohm-cm)	Measured 56-Day SR (kilohm-cm)	91-Day SR Predicted by 28-Day SR Equation (kilohm-cm)	91-Day SR Predicted by 56-Day SR Equation (kilohm-cm)	Measured 91-Day SR (kilohm-cm)
S-6	30.9	41.0	40.4	50.7	49.9	46.5
S-7	31.4	41.6	40.8	51.4	50.3	45.4
S-8	33.8	44.4	45.0	54.5	54.9	53.9
S-9	32.6	43.0	44.0	52.9	53.8	51.0
S-10	31.5	41.7	50.2	51.5	60.6	50.7
S-11	31.8	42.1	48.7	51.9	58.9	50.5
S-12	32.9	43.4	47.2	53.3	57.3	64.7
S-13	29.4	39.2	43.9	48.8	53.7	61.1
S-14	29.0	38.7	39.3	48.2	48.6	50.8
S-15	29.6	39.4	39.2	49.0	48.5	48.0
S-16	32.1	42.4	43.5	52.3	53.2	49.2
S-17	29.9	39.8	39.6	49.4	49.0	46.2
S-18	33.3	43.8	47.1	53.8	57.2	51.5
S-19	32.0	42.3	44.5	52.1	54.3	51.6
S-20	33.3	43.8	43.2	53.8	52.9	51.9
S-21	32.3	42.6	42.4	52.5	52.0	50.6
S-22	30.9	41.0	39.6	50.7	49.0	46.6
S-23	30.3	40.3	38.1	49.9	47.3	45.7
S-24	32.9	43.4	42.1	53.3	51.7	55.6
S-25	31.4	41.6	41.3	51.4	50.8	56.5

TABLE AM.3: Effect of SCM on SR Study SR Predicted and Measured Results with Additional Results

ID #	Measured 28-Day SR (kilohm-cm)	56-Day SR Predicted by 28-Day SR Equation (kilohm-cm)	Measured 56-Day SR (kilohm-cm)	91-Day SR Predicted by 28-Day SR Equation (kilohm-cm)	91-Day SR Predicted by 56-Day SR Equation (kilohm-cm)	Measured 91-Day SR (kilohm-cm)
20F – 1	12.4	18.9	17.7	26.7	25.0	29.2
20F – 2	13	19.6	18.1	27.4	25.5	29.3
20F – 3	13.2	19.9	17.9	27.7	25.2	28.5
25F – 1	14.1	20.9	22.1	28.9	29.8	36
25F – 2	14.3	21.2	22.5	29.1	30.3	34.9
25F - 3	14	20.8	22.1	28.7	29.8	34.9
25C – 1	12.5	19.0	17.8	26.8	25.1	27.9
25C – 2	12.8	19.4	18.2	27.2	25.6	28.3
25C – 3	12.7	19.3	18	27.0	25.4	28
3.5SF20F - 1	27.5	36.9	43.3	46.3	53.0	58.1
3.5SF20F – 2	28.1	37.6	44.8	47.1	54.7	59.3
3.5SF20F – 3	28.4	38.0	45	47.5	54.9	59.7
5SF25C – 1	31.1	41.2	53.2	51.0	63.9	70.5
5SF25C – 2	30.3	40.3	50.3	49.9	60.7	66.1
5SF25C – 3	29.3	39.1	49.1	48.6	59.4	64.4
3.5MK20F - 1	30.9	41.0	40.1	50.7	49.5	51
3.5MK20F - 2	29.7	39.5	37.7	49.1	46.9	49.1
3.5MK20F – 3	29.3	39.1	37.3	48.6	46.5	47.2
5MK25C – 1	33.1	43.6	41.5	53.6	51.1	50.7
5MK25C – 2	33.1	43.6	41	53.6	50.5	49.1
5MK25C - 3	32.8	43.2	40.6	53.2	50.1	48.6
45SL – 1	29.9	39.8	35.9	49.4	44.9	44.1
45SL – 2	30.9	41.0	36.9	50.7	46.0	45.3
45SL – 3	32.7	43.1	38	53.0	47.2	47.9
35SL15F – 1	31.8	42.1	45.2	51.9	55.1	55
35SL15F – 2	31.8	42.1	45.1	51.9	55.0	55
35SL15F – 3	30.6	40.6	44.1	50.3	53.9	53.3

TABLE AM.4: Effect of SCM on SR Study SR Predicted and Measured Results with Additional Results Continued

ID #	Measured 28-Day SR (kilohm-cm)	56-Day SR Predicted by 28-Day SR Equation (kilohm-cm)	Measured 56-Day SR (kilohm-cm)	91-Day SR Predicted by 28-Day SR Equation (kilohm-cm)	91-Day SR Predicted by 56-Day SR Equation (kilohm-cm)	Measured 91-Day SR (kilohm-cm)
100PC – 1	12.3	18.8	14.6	26.5	21.6	17.8
100PC – 2	11.5	17.8	13.3	25.5	20.2	16.3
100PC - 3	12	18.4	14	26.1	21.0	16.7
45SL5MK – 1	101.4	125.1	114.2	142.3	130.6	127.8
45SL5MK – 2	100.5	124.0	114.2	141.2	130.6	124.4
45SL5MK – 3	101.1	124.7	115.8	141.9	132.3	125.5
35SL15MK – 1	139.7	170.7	172.2	192.1	194.0	196.8
35SL15MK – 2	137.9	168.6	172.7	189.8	194.5	197.3
35SL15MK – 3	139.7	170.7	177.6	192.1	199.9	205.3
50C – 1	13.1	19.7	22.6	27.6	30.4	34.3
50C – 2	13	19.6	21.8	27.4	29.5	31.5
50C - 3	12.6	19.2	21.4	26.9	29.1	31.6

TABLE AM.5: TTU Slag Study SR Predicted and Measured Results with Additional Results

ID #	Measured 56-Day SR (kilohm-cm)	91-Day SR Predicted by 56-Day SR Equation (kilohm-cm)	Measured 91-Day SR (kilohm-cm)
50/25/25F-1	59	70.2	67.7
50/25/25F-2	56.9	67.9	65.6
50/30/20F-1	52.0	62.5	61.0
50/30/20F-2	52.8	63.4	60.9
50/35/15F-1	52.6	63.2	67.8
50/35/15F-2	55.7	66.6	67.6
50/25/25C-1	44.4	54.2	54.9
50/25/25C-2	43.5	53.2	53.7
50/30/20C-1	40.1	49.5	43.3
50/30/20C-2	39.7	49.1	43.3
50/35/15C-1	50.0	60.4	54.5
50/35/15C-2	46.9	57.0	59.0