Final Report June 2007

UF Project No. 00026899
Contract No. BD536

PERMEABILITY OF CONCRETE – COMPARISON OF CONDUCTIVITY AND DIFFUSION METHODS

Principal Investigator:	H. R. Hamilton III, P.E., Ph.D.
Co-Principal Investigator:	Andrew J. Boyd, Ph.D.
Graduate Research Assistant:	Enrique Vivas
Project Manager:	Michael Bergin, P.E.

Department of Civil & Coastal Engineering
College of Engineering
University of Florida
Gainesville, Florida 32611

Engineering and Industrial Experiment Station

STATE OF FLORIDA • DEPARTMENT OF TRANSPORTATION

DISCLAIMER

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Permeability of Concrete – Comparison of Conductivity And Diffusion Methods	5. Report Date June 2007
	6. Performing Organization Code
7. Author(s) E. Vivas, A. Boyd, and H. R. Hamilton III	8. Performing Organization Report No. 4910 45 04 992-12 (00026899)
9. Performing Organization Name and Address University of Florida Department of Civil & Coastal Engineering P.O. Box 116580 Gainesville, FL 32611-6580	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. BD 536
12. Sponsoring Agency Name and Address Florida Department of Transportation Research Management Center 605 Suwannee Street, MS 30 Tallahassee, FL 32301-8064	13. Type of Report and Period Covered Final Report 3/5/03-11/30/06
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report details research conducted on methods used to rapidly determine the resistance of concrete to the penetration of chloride ions. These methods, based on the electrical conductivity of concrete were Rapid Chloride Permeability (RCP) (AASHTO T277, ASTM C1202), Rapid Migration Test (RMT) (NordTest NTBuild 492), Surface Resistivity (SR) (FM 5-578), and Impressed Current (FM 5-522). The results of these conductivity tests were compared to the Bulk Diffusion (NordTest NTBuild 443) and AASHTO T259 test methods, which allow a more natural penetration of the concrete by the chlorides.

Nineteen different mixtures were prepared using materials typically used in construction in the State of Florida. Twelve mixtures were laboratory prepared and the remaining seven mixtures were obtained at various field sites around the State. The concrete mixtures were designed to have a range of permeabilities. Some of the designs included such pozzolans as fly ash and silica fume. One mixture was prepared with calcium nitrate corrosion inhibitor.

Diffusion coefficients were determined from both the Bulk Diffusion (BD) and AASHTO T259 tests using a 364-day chloride exposure period. Two procedures were used to evaluate the data collected from the AASHTO T259 test; total integral chloride content and by fitting the data to Fick's Second Law of diffusion equation to obtain an apparent diffusion coefficient. The electrical results from the short-term tests RCP, SR and RMT at 14, 28, 56, 91, 182 and 364 days of age were then compared to the two long-term diffusion reference tests. It was found that correlations between the RMT and the long-term tests were equal or slightly better than those obtained by the RCP and SR tests. RMT test was found to be less effected by the presence of supplementary cementitious materials and was applicable to wider range mineral admixtures in concrete than the RCP and SR tests.

The surface resistivity test was conducted using two methods of curing, one at 100% humidity (moist cured) and the other in a saturated lime solution. The comparison of results of the SR tests between the two curing procedures showed no significant differences. Therefore, it was concluded that either of the methods will provide similar results.

A new calibrated scale to categorize the equivalent RCP measured charge in coulombs to the chloride ion permeability of the concrete was developed. The proposed scale was based on the correlation of the 91-day RCP results related to the chloride permeability measured by a 364-day Bulk Diffusion test.

17. Key Word Concrete Durability, Permeability, Diffusion, Colorimetric Method, Conductivity, Resistivity, RCP Limits.	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA, 22161

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 238	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGMENTS

The authors would like to acknowledge and thank the Florida Department of Transportation for providing the funding for this research project. This project was a collaborative effort among the University of Florida, and the FDOT State Materials Office Research Laboratory (Gainesville). Special thanks to Mario Paredes, FDOT State Materials Corrosion Office, for his guidance and technical support during the course of the project. Moreover, the authors would like to thank the FDOT State Materials Office Research Laboratory personnel for constructing the specimens and conducting materials testing, especially Charlotte Kasper, Phillip Armand and Sandra Bober, whose help was critical to the completion of this project. The assistance of Elizabeth (Beth) Tuller, Robert (Mitch) Langley and Richard DeLorenzo is gratefully acknowledged. The authors express their sincere gratitude to Dennis Baldi and Luke Mcleod who assisted in the field investigations of the project. Moreover, the assistance of staff from FDOT Districts (D2, D3, D4, D5 and D7) for their assistance in the field investigations; especially Bobby Ivery, Steve Hunt, Wilky Jordan, Ken Gordon, Donald Vanwhervin, Daniel Haldi and Keith West. The authors would like to thank CEMEX, BORAL Materials Technologies Inc., W.R. Grace & Co., Burgess Pigment Co., Lafarge, RINKER Materials Corp., S. Eastern Prestress Concrete Inc., Gate Concrete Products and COUCH Concrete for their contributions to this research.

Executive Summary

Reinforced concrete structures exposed to a marine environment often deteriorate in the early stages of their service life due to corrosion of the reinforcing steel. Chloride ions penetrate the concrete and upon reaching the steel reinforcement cause a rapid increase in corrosion rate. Consequently, the chloride penetration resistance of the concrete surrounding the reinforcement is a critical parameter in determining the long-term performance of structures in a marine environment.

This report details research conducted on methods used to rapidly determine the resistance of concrete to the penetration of chloride ions. These methods, based on the electrical conductivity of concrete were Rapid Chloride Permeability (RCP) (AASHTO T277, ASTM C1202), Rapid Migration Test (RMT) (NordTest NTBuild 492), Surface Resistivity (SR) (FM 5-578), and Impressed Current (FM 5-522). The results of these conductivity tests were compared to the Bulk Diffusion (NordTest NTBuild 443) and AASHTO T259 test methods, which allow a more natural penetration of the concrete by the chlorides.

Nineteen different mixtures were prepared using materials typically used in construction in the State of Florida. Twelve mixtures were cast at the FDOT State Materials Office (SMO) in Gainesville and the remaining seven mixtures were obtained at various field sites around the State. The concrete mixtures were designed to have a range of permeabilities. Some of the designs included such pozzolans as fly ash and silica fume. One mixture was prepared with calcium nitrate corrosion inhibitor.

Bulk Diffusion (BD) and AASHTO T259 tests were conducted with a 364-day chloride exposure period. Diffusion coefficients calculated from BD test results were determined by fitting the data obtained from the chloride profiles to Fick's second law of diffusion equation. Two procedures were used to evaluate the data collected from the AASHTO T259 test; total integral chloride content and by fitting the data to Fick's Second Law of diffusion equation to obtain an apparent diffusion coefficient. The electrical results from the short-term tests RCP, SR and RMT at 14, 28, 56, 91, 182 and 364 days of age were then compared to the two long-term diffusion reference tests. It was found that total integral chloride content results did not correlate well with that of the Bulk Diffusion coefficients (R^2 of 0.339). Comparison of the long-term diffusion coefficients gave an R^2 value of 0.829. Therefore, Fick's Diffusion Second Law approximation was selected as more appropriate method of analysis for AASHTO T259 method.

Correlations between the RMT and the long-term tests were equal or slightly better than those obtained by the RCP and SR tests. RMT test was found to be less effected by the presence of supplementary cementitious materials. The test was applicable to wider range mineral admixtures in concrete than the RCP and SR tests.

The accuracy and sensibility of the standard colorimetric method recommended by the RMT test for measuring the depth chloride infiltration was evaluated. A comparison study between the corresponding chloride concentrations to the color-change boundary of the colorimetric silver nitrate method was made. A set of 63 samples were axially split; chloride content was measured on one half with FM 5-516 and colorimetric penetration was calculated on the other half by spraying silver nitrate solution. An average chloride concentration by weight of concrete of 0.14% was found by this evaluation. On the other hand, it presents quite a high coefficient of variation of 40.28%.

The surface resistivity test was conducted using two methods of curing, one at 100% humidity (moist cured) and the other in a saturated $Ca(OH)_2$ solution (lime cured). The comparison of results of the SR tests between the two curing procedures showed no significant differences. Therefore, it was concluded that either of the methods will provide similar results.

The level of agreements (R^2) obtained for all the short-term tests to the references showed that the best testing age for a RCP, SR and RMT test to predict a 364-day Bulk Diffusion test is 91 days and 364 days to predict a 364-day AASHTO T259 test.

A new calibrated scale to categorize the equivalent RCP measured charge in coulombs to the chloride ion permeability of the concrete was calculated. The proposed scale was based on the correlation of the 91-day RCP results related to the chloride permeability measured by a 364-day Bulk Diffusion test.

To provide additional data to which laboratory results can be corroborated, sample specimens collected from recently constructed FDOT bridges located in marine environments were surveyed. Six bridge substructures that meet the FDOT specifications (FDOT 346 2004) for concrete elements under extremely aggressive environments were selected. A total of 14 core samples were obtained from undamaged concrete near the tide lines. The cores were then sliced or ground and chloride content was measured to produce a profile, from which the diffusion coefficients were calculated.

Table of Contents

List of Figures

List of Tables

1 INTRODUCTION

Reinforced concrete structures exposed to a marine environment often deteriorate in the early stages of their service life. The main reason is corrosion of the reinforcing steel due to the penetration of chloride ions through the concrete. Therefore, the chloride penetration resistance of concrete is a critical parameter in determining the long-term performance of structures in a marine environment. Several standardized tests can be used to determine the resistance to chloride penetration in concrete. The short-term conductivity test, Rapid Chloride Permeability (RCP), is one of the most widely used, because its results correlate reasonably well with those from long-term 90-day ponding tests. The test can, however, give misleading results when used on samples containing pozzolans or corrosion inhibitors.

To address these inconsistencies, several alternative test procedures were evaluated within the outline of the basic test methodology of the RCP. The test that gave the best results was a relatively new procedure called the Rapid Migration Test (RMT). In all cases, the correlations between the RMT and the long-term test were equal or slightly better than those obtained by the RCP. The RMT was also applicable to a wider range of chemical and mineral admixtures in concrete than the RCP.

This report details results of a research project funded by the Florida Department of Transportation (FDOT) to evaluate currently available conductivity tests and compare the results of these tests to those from long-term diffusion tests. Moreover, to provide additional data to which laboratory results can be corroborated, sample specimens collected from recently constructed FDOT bridges located in marine environments will be surveyed. This report includes a literature review, descriptions of the test methods, concrete mixture designs, and results of the laboratory experimentations. Finally, the report presents final conclusions and recommendations concerning allowable limits on the test procedures for future FDOT standard specifications.

1.1 RESEARCH OBJECTIVES

The primary objective of this research was to compare the RMT and surface resistivity methods to other standard test methods for chloride penetration. This will determine their usefulness in evaluating concrete mixture designs in the State of Florida. The report presents final conclusions and recommendations concerning allowable limits on the test procedures for future FDOT standard specifications.

2 LITERATURE REVIEW

2.1 MECHANISM OF CHLORIDE ION TRANSPORT

There are four fundamental modes that chloride ions are transported through concrete. They are diffusion, capillary absorption, evaporative transport and hydrostatic pressure. Diffusion is the movement of chloride ions under a concentration gradient. It will occur when the concentration of chlorides on the outside of the concrete member is greater than on the inside. The chlorides ions in concrete will naturally migrate from the regions of high concentration (high energy) to the low concentration (low energy) as long as sufficient moisture is present along the path of migration. This process can be modeled mathematical by Fick's First and Second Law of Diffusion (APPENDIX B). Moreover, it is the principal mechanism that drives chloride ions into the pore structure of concrete (Tuutti 1982; Stanish and Thomas 2003).

Capillary absorption occurs when the dry surface of the concrete is exposed to moisture (perhaps containing chlorides). The solution is drawn into the porous matrix of the concrete by capillary suction, much like a sponge. Generally, the shallow depth of chloride ion penetration by capillary action will not reach the reinforcing steel. It will, however, reduce the distance that chloride ions must travel by diffusion (Thomas, Pantazopoulou and Martin-Perez 1995).

The evaporative transport mechanism, also known as wicking effect, is produced by vapor conduction from a wet side surface to a drier atmosphere. This is a vapor diffusivity process where a retained body of liquid in the pore structure of the concrete evaporates and leaves deposits of chlorides inside. For this mechanism to occur, it is necessary that one of the surfaces be air-exposed.

Another mechanism for chloride ingress is permeation, driven by hydrostatic pressure gradients. A hydrostatic pressure gradient can provide the required force to move liquid containing chlorides ions through the internal concrete matrix. An external hydrostatic pressure can be supplied by a constant wave action or by a retained body of water like bridges, piers, dams, etc. that are exposed to a marine environment (Chini, Muszynski and Hicks 2003).

2.2 PERMEABILITY MEASUREMENT OF THE CONCRETE

Permeability is defined as the resistance of the concrete to chloride ion penetration. Several researchers (Dhir and Byars 1993; Li, Peng and Ma 1999; Page, Short and El Tarras 1981) have attempted to capture the natural diffusion of chlorides through the concrete pore structure by immersing or ponding samples with salt solution. These test methods, however, require considerable time to obtain a realistic flow of chlorides. Consequently, numerous accelerated test procedures have been designed to predict the penetration of chloride ions. The accelerated methods permit diffusion rates to be established for a specific mixture design in a relatively short time period. The migration of chlorides through the sample is generally accelerated by the application of an electrical potential, forcing the chloride ions through the sample at an accelerated rate.

This section will discuss the testing procedures that have been selected for the research as more representative methods to calculate the permeability of the concrete against chloride ion ingress. It will identify what has been done before the present study to prelude the current study's contribution to future research. The review of various types of approaches for gathering and analyzing data will help to justify the value, importance, and necessity of this study.

2.2.1 90-DAY SALT PONDING TEST (AASHTO T259)

AASHTO T259 has been traditionally the most widely used method of determining the actual resistance of concrete to chloride ion penetration. For this test, three concrete slabs measuring 3-inch (76-mm) thick and 12-inch (305-mm) square are used. These slabs are moist cured for 14 days and then kept for an additional 28 days in a drying room with a 50 percent relative humidity environment. A dam is affixed to the non-finished face of the slab and a 3 percent NaCl solution is ponded on the surface, leaving the bottom face of the slabs exposed to the drying environment (see Figure 1). The specimens are maintained with a constant amount of the chloride solution for a period of 90 days. They are removed from the drying room and chloride ion content of half-inch thick slices is determined according to AASHTO T 260 (Standard Method of Test for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials).

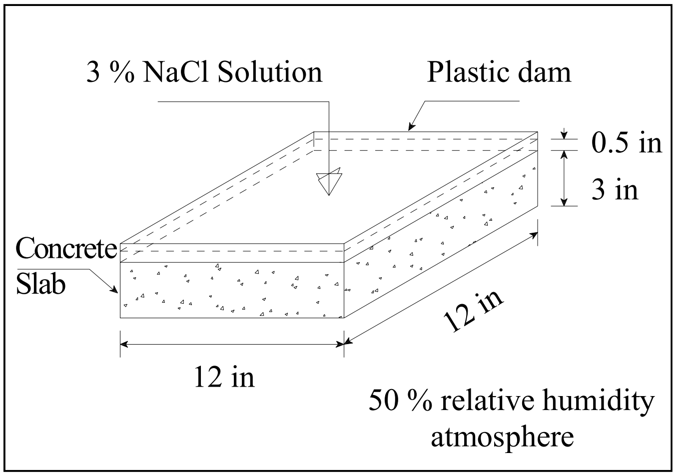


Figure 1. Ninety-day Salt Ponding Test Setup (AASHTO T259).

The ponding test has several limitations. The complete test takes at least 118 days to complete (moist cured for 14 days, dried for 14 days and ponded for 90 days). This means that the chloride permeability samples must be cast at least four months before a particular concrete mixture will be used in the field. In addition, the 90-day ponding period is often too short to allow sufficient chloride penetration in higher strength concrete. Pozzolans such as fly ash or silica fume have been shown to greatly reduce the permeability of concrete, thus reducing the penetration of chlorides over the 90-day test period (Scanlon and Sherman 1996). Consequently, an extended ponding time is generally necessary to ensure sufficient penetration of chloride ions (Hooton, Thomas and Stanish 2001; Scanlon and Sherman 1996).

Another drawback of this test method is that sampling every 0.5 inch (13 mm) does not provide a fine enough measurement to allow for determination of a profile of the chloride penetration. Only the average of the chloride penetration in those slices is obtained, not the actual variation of the chloride concentration over that 0.5 inch (13 mm) (Hooton, Thomas and Stanish 2001). The actual penetration depth is a more useful measurement rather than an average chloride content as measured in the slices (Hooton 1997). This is particularly important in low permeability concrete where the chloride content can change drastically over a short length.

The ponding test forces chloride intrusion through immediate absorption; long-term diffusion of chloride into the concrete under a static concentration gradient; and wicking due to drying from the exposed surface of the specimen (Scanlon and Sherman 1996). Since the sample initially has to be dried for 28 days, an absorption effect occurs when it is first exposed to the NaCl solution by capillary suction, pulling chlorides into the concrete (Glass and Buenfeld 1995). During the ponding process one of the exposed faces is submerged in the solution while the other is exposed to air at 50 percent relative humidity (presumably to model the underside of a bridge deck). This creates vapor conduction (wicking) from the wet side face of the sample to the drier face, which enhances the natural diffusion of the chloride ions. There is still some controversy concerning the relative importance of these mechanisms in actual field conditions. McGrath and Hooton (1999) have suggested that the relative importance of the absorption effect is overestimated.

2.2.2 BULK DIFFUSION TEST (NORDTEST NTBUILD 443)

The bulk diffusion procedure was developed in order to address some of the problems with the 90-day salt ponding test. The test was standardized as a Nordtest procedure (an organization for test methods in the Nordic countries). The main focus of the modifications was to attain a better controlled "diffusion only" test with no contribution from absorption or wicking effects (Hooton, Thomas and Stanish 2001). This will improve the precision of the profile obtained for the simulation of a long-term chloride penetration. The method can be applied to new samples or samples taken from existing structures.

The sample configuration used for this procedure is a 4-inch (102-mm) diameter by 4-inch (102-mm) long concrete cylinder. In contrast to AASHTO T259, the specimens are immediately placed in a saturated limewater solution after a 28 days moist cured period. This wet condition prevents the initial sorption when the solution first contacts the specimen. Furthermore, the sample is sealed on all faces except the one that is exposed to the 2.8 M NaCl solution (16.5% NaCl) (see Figure 2). The test procedure calls for an exposure period of at least 35 days for lower-quality concretes (NTBuild 443 1995). For higher-quality concrete mixtures, the exposure time must be extended to at least 90-days.

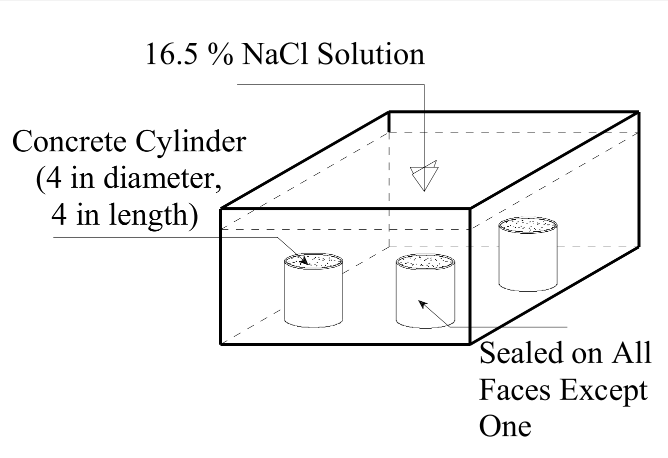


Figure 2. Bulk Diffusion Test Setup (NordTest NTBuild 443).

The chloride profiles are performed immediately after the exposure period. The profile layers are obtained by grinding the sample with a diamond-tipped bit. The benefit of pulverizing the profile by this method is the accuracy of depths that can be attained. Chloride profiles with depth increments on the order of 0.02 inch (0.5 mm) can be attained. The actual chloride penetration depth calculated by this method gives more resolution than the 0.5-inch (13-mm) layers obtained from 90-day salt ponding test procedure.

2.2.3 RAPID CHLORIDE PERMEABILITY (AASHTO T277, ASTM C1202)

The rapid chloride permeability test (RCP) is one of the short-term procedures most widely used to assess concrete durability. The test is, however, a measurement of the electrical conductivity of concrete, rather than a direct measure of concrete permeability. Nonetheless, its results correlate reasonably well with those from the long term 90-day salt ponding test (Whiting 1981). More recent research has found inconsistent test results when the samples contained pozzolans or corrosion inhibitors (Pfeifer, McDonald and Krauss 1994; Scanlon and Sherman 1996 and Wee, Suryavanshi and Tin 2000).

The test method describes the measurement of electrical conductance by subjecting a 4-inch (102-mm) diameter by 2-inch (51-mm) thick saturated sample to a 60-volt DC potential for a period of six hours. One side of the specimen is immersed in a reservoir with a 3.0 percent NaCl solution, and the other side to another reservoir containing a 0.3 N NaOH solution (1.2% NaOH) (see Figure 3). The cumulative electrical charge, measured in coulombs, represents the current passed through the concrete sample during the test period. The area under the current versus time curve was found to correlate with the resistance of the specimen to chloride ion penetration (Whiting 1981). According to ASTM C1202, permeability levels based on charge passed through the sample are presented on Table 1.z

Table 1. Comparison of RCP Results with Ponding Tests (AASHTO T277, ASTM C1202) (Whiting 1981).

Chloride Permeability	**Charge (Coulombs)**	**Type of Concrete**	**Total Integral Chloride to 41 mm Depth After 90-day Ponding Test**
High	> 4,000	High water-to-cement ratio (>0.6) conventional Portland cement concrete	>1.3
Moderate	2,000-4,000	Moderate water-to-cement ratio (0.4-0.5) conventional Portland cement concrete	0.8 -1.3
Low	1,000-2,000	Low water-to-cement ratio (<0.4) conventional Portland cement concrete	0.55 – 0.8
Very Low	100-1,000	Latex modified concrete, internally sealed concrete	0.35 – 0.55
Negligible	<100	Polymer impregnated concrete, polymer concrete	<0.35

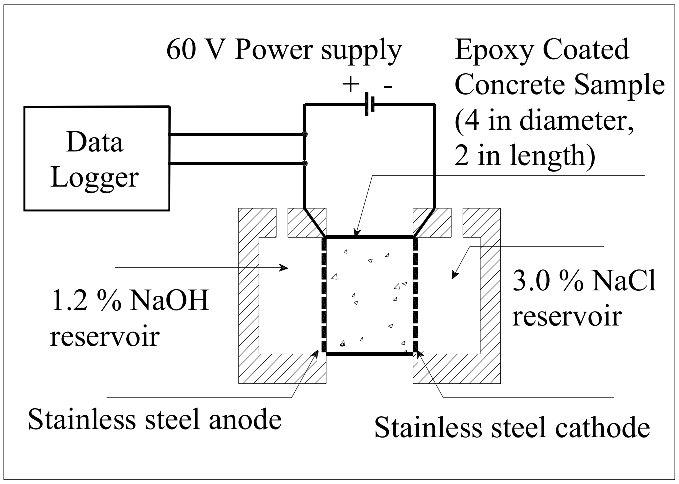


Figure 3. Rapid Chloride Permeability Test Setup (AASHTO T277, ASTM C1202).

The RCP test has received much criticism from researchers during the past decade for inconsistencies found when the electrical resistivity-based measurements obtained are compared with diffusion-based test procedures like the 90-day salt ponding test (Andrade 1993; Feldman et al. 1994; Pfeifer, McDonald and Krauss 1994; Scanlon and Sherman 1996 and Shi, Stegemann and Caldwell 1998; Shi 2003). One of the main criticisms is that permeability depends on the pore structure of the concrete, while electrical conductivity of the water saturated concrete depends not only on the pore structure but also the chemistry of pore solution. Changes in pore solution chemistry generate considerable alterations in the electrical conductivity of the sample. These variations can be produced by adding fly ash, silica fume, metakaoline or ground blast furnace slag. Silica fume, metakaoline and ground blast furnace slag are reactive materials that may considerably improve the pore structure and reduce the permeability of the concrete. This is not the case with fly ash, however, because it is slow reacting and generally reduces permeability by only 10 to 20% at 90 days. In addition, the reduction in charge passed in the presence of fly ash is mainly due to a reduction of pore solution alkalinity, rather than a reduction in the permeability of the concrete (Shi 2003).

Another criticism is that the high voltage of 60 volts applied during the test leads to an increase in temperature, especially for a low quality concrete, which may result in an apparent increase in the permeability due to a higher charge being passed (McGrath and Hooton 1999; Snyder et al. 2000 and Yang, Cho and Huang 2002). Several modifications to the procedures have been proposed to minimize the temperature effect. One (Yang, Cho and Huang 2002) proposes an increase in the standardized acrylic reservoirs from 250 ml (as recommended by ASTM C1202) to 4750 ml. It was found that the chloride diffusion coefficient from RCP reached a steady-state after chloride-ions pass through the specimen. Another modification is to record the charge passed at the 30-minute mark and linearly extrapolate to the specified test period of 6 hours (McGrath and Hooton 1999).

The standardized RCP test method, ASTM C1202, is commonly required by construction project specifications for both precast and cast-in-place concrete. An arbitrary value, chosen from the scale shown on Table 1, of less than 1000 coulombs is usually specified by the engineer or owner for concrete elements under extremely aggressive environments (Pfeifer, McDonald and Krauss 1994). This low RCP coulomb limit is required by the Florida Department of Transportation (FDOT) when Class V or Class V Special concrete containing silica fume or metakaolin as a pozzolan is tested on 28 days concrete samples (FDOT 346 2004).

2.2.4 Rapid Migration Test (NordTest NTBuild 492)

General agreement on the best short-term test method has not been reached. A promising test procedure, the Rapid Migration Test (RMT), has recently been introduced as an alternative to the commonly used but flawed RCP test. This test was originally proposed by Luping Tang and Lars-Olof Nilsson at Chalmers Technical University in Sweden (Tang and Nilsson 1992) and it is believed by some researchers to be a reliable test procedure (Streicher and Alexander 1994). The test procedure can be carried out with a similar apparatus as is used to conduct the RCP (see Figure 4). The RMT involves subjecting a 4-inch (102-mm) diameter by 2-inch (51-mm) thick saturated samples to an external electrical potential to force chlorides ions to migrate into the specimens (NT BUILD 492 1999). To account for varying concrete resistances, the initial current flow through the specimen is measured and the applied voltage is adjusted accordingly. The samples are fit into silicone rubber sleeves where one of the sides of the specimens is immersed in a 0.3 N NaOH (1.2% NaOH) solution and the other side to a 10 percent NaCl solution. After a specified duration, the samples are removed and axially split into two pieces. A depth of chloride penetration is determined in one half of the specimen using a colorimetric technique; spraying silver nitrate solution on the freshly cut surface.

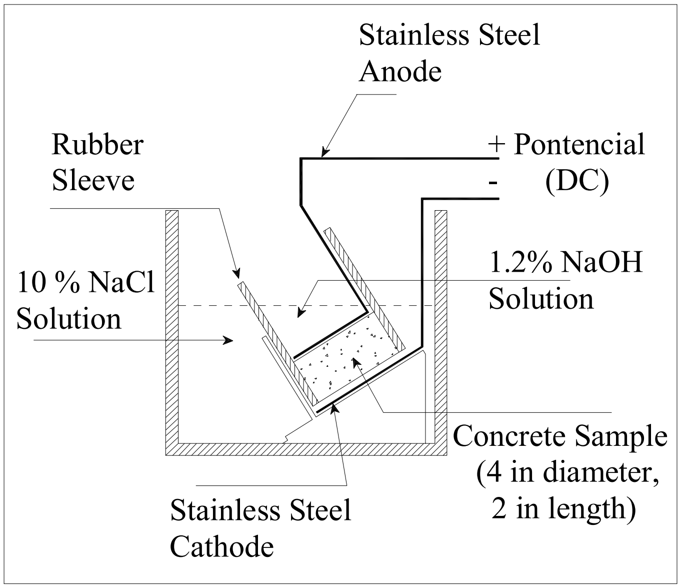


Figure 4. Rapid Migration Test Setup (NordTest NTBuild 492).

The originally proposed method called for the concrete sample to be exposed to a voltage gradient for 8 hours, after which the specimen is sliced and sprayed with an indicator for chlorides, $AgNO_3$ to determine the depth of chloride penetration. This time period makes the procedure difficult to fit into a normal working day of a laboratory. Consequently, Tang and Nilsson revised their method to use varying voltages and test durations depending upon the initial current measured (NTBuild 492) (see Table 2). This improved test was standardized as a Nordtest procedure.

The standardized method NTBuild 492 still presented further problems. The most critical is the extended time duration of the test (as long as 4 days in some cases) and the wide range of applied voltage that must be used. A simplified testing protocol was developed in which the effect of several different voltages and test durations were evaluated (Hooton, Thomas and Stanish 2001). Based on the results of their research, a fixed test duration of 18 hours was selected, with a varying applied voltage. The voltage selected for the test is based on the initial current values for that sample under a 60-volt potential (see Table 3). The new proposed voltage values were selected to avoid chloride breakthrough that would occasionally occur in the NTBuild 492 procedure (see Table 2).

Table 2. Test voltage and duration for Standard NTBuild 492 Test (Hooton, Thomas and Stanish 2001)

Initial Current @ 30V [mA]	**Applied Voltage [Volts]**	**Test Duration [hr]**	**Expected Penetration [mm]**	**V*t [V-hr]**
< 5	60	96	< 23	5,760
5-10	60	48	12-20	2,880
10-15	60	24	10-15	1,440
15-20	50	24	12-16	1,200
20-30	40	24	12-18	960
30-40	35	24	15-21	840
40-60	30	24	18-27	720
60-90	25	24	22-33	600
90-120	20	24	26-35	480
120-240	15	24	26-54	360
240-400	10	24	36-77	240
400-600	10	24	36-77	240
> 600	10	6	> 19	60

The evaluation test program at the University of Toronto (Hooton, Thomas and Stanish 2001) found that the results from RMT are less affected by the conductive ions in the concrete pore solution when supplementary cementitious materials (such as fly ash, silica fume or ground granulated blast-furnace slag) are present. Moreover, it shows that the test procedure did not appear to be affected by the presence of calcium nitrite corrosion inhibitor. In general, the correlations between the RMT and the long-term tests were equal or slightly better than those achieved by the RCP test, showing that the RMT test can be apply to a wider range of concrete mixtures than the RCP test.

Table 3. Test voltage and duration proposed by Hooton, Thomas and Stanish 2001

Initial Current @ 60V [mA]	Applied Voltage [Volts]	Test Duration [hr]	Expected Penetration [mm]	V*t [V-hr]
< 10 10-20 20-30 30-40 40-60 60-80 80-120	60	18	< 40	1,080
120-180 180-240	30	18	20-40	540
240-480 480-800	10	18	13-40	180
800-1,200 > 1,200	No Test	No Test	No Test	No Test

2.2.5 COLORIMETRIC CHLORIDE PENETRATION DEPTH TECHNIQUE

Several test methods to determine the chloride content in concrete have been developed. Fluorescent x-ray analysis (Tertian and Claisse 1982), stirring extraction method and acid – soluble chloride-ion content (ASTM C1152/C1152M) are some of the most commonly used. These procedures for measuring the chloride profiles, however, are very time consuming. Another easier and quicker analysis that can be performed is the colorimetric method. This procedure is based on spraying a 0.1M silver nitrate aqueous solution on a cross-section of split concrete to determine the depth of chloride penetration. The sprayed solution creates a chemical reaction where the chlorides present in the concrete react and produce a visibly clear white or silver precipitate (due to precipitation of AgCl). A brownish color is created on the surface where the silver nitrate solution, in the absence of chlorides, reacted instead with the hydroxides present in the concrete.

The accuracy and sensibility of the colorimetric procedure is still questionable. The measured white colorimetric front seems to represent how far the free and acid-soluble chloride has penetrated into concrete. The lack of agreement concerning chloride ion concentration of these free ions corresponding to the color-change boundary represents the main issue of the method (Andrade et al. 1999; Meck and Sirivivatnanon 2003). Otsuki et al. (1992) reported a relatively constant value of 0.15% of water-soluble chloride concentration by weight of cement for the investigated pastes, mortar and concrete with different water/cement ratios. The coefficient of variation of the studied values was not reported. On the other hand, subsequent researches have found high variability in the water-soluble chloride concentrations correlations with the color-change boundary (Sirivivatnanon and Khatri 1998; Andrade et al. 1999; Meck and Sirivivatnanon 2003) (see Table 4).

Table 4. Average Chloride Concentrations Found at the Color-Change Boundary and Statistical Parameters by Different Research (Sirivivatnanon and Khatri 1998; Andrade et al. 1999; Meck and Sirivivatnanon 2003).

	Acid-Soluble Chloride Concentrations					
	Min	**Max**	**Average**	**Standard Deviation**	**Coefficient of Variation**	**Number of Observations**
Sirivivatnanon and Khatri 1998						
% by Weight of Concrete	0.02	0.23	0.12	0.05	40	74
% by Weight of Binder	0.28	1.41	0.9	0.3	33	36
Andrade et al. 1999						
% by Weight of Concrete	-	-	0.18	-	49	11
% by Weight of Binder	-	-	1.13	-	-	11
Meck and Sirivivatnanon 2003						
% by Weight of Binder	0.84	1.69	1.2	-	27	-

2.2.6 SURFACE RESISTIVITY TEST USING THE FOUR-POINT WENNER PROBE (FM 5-578)

Concrete conductivity is fundamentally related to the permeability of fluids and the diffusivity of ions through a porous material (Whiting and Mohamad 2003). As a result, the electrical resistivity can be used as an indirect measure of the ease in which chlorides ions can penetrate concrete (Hooton, Thomas and Stanish 2001). The resistivity of a saturated porous medium, such as concrete, is mainly measured by the conductivity through its pore solution (Streicher and Alexander 1995).

Two procedures have been developed to determine the electrical resistivity of concrete. The first method involves passing a direct current through a concrete specimen placed between two electrodes. The concrete resistance between the two electrodes is measured. The actual resistance measured by this method can be reduced by an unknown amount due to polarization at the probe contact interface. The second method solves the polarization problem by passing an alternating current (AC) through the sample. A convenient tool to measure using this method is the four-point Wenner Probe resistivity meter (Hooton, Thomas and Stanish 2001). The set up utilizes four equally spaced surface contacts, where a small alternating current is passed through the concrete sample between the outer pair of contacts. A digital voltmeter is used to measure the potential difference between the two inner electrodes, obtaining the resistance from the ratio of voltage to current (see Figure 5). This resistance is then used to calculate resistivity of the section. The resistivity ρ of a prismatic section of length L and section area A is given by:

$$\rho = \frac{A.R}{L}$$

where R is the resistance of the specimen calculated by dividing the potential V by the applied current I.

The resistivity ρ for a concrete cylinder can be calculated by the following formula:

$$\rho = \left(\frac{\pi . d^2}{4}\right)\frac{1}{L}\cdot\left(\frac{V}{I}\right)$$

where d is the cylinder diameter and L its length (Morris, Moreno and Sagües 1996).

Assuming that the concrete cylinder has homogeneous semi-infinite geometry (the dimensions of the element are large in comparison of the probe spacing), and the probe depth is far less than the probe spacing, the concrete cylinder resistivity ρ is given by:

$$\rho = (2.\pi . a)\cdot\left(\frac{V}{I}\right)$$

where a is the electrode spacing (see Figure 5). The non-destructive nature, speed, and ease of use make the Wenner Probe technique a promising alternative test to characterize concrete permeability.

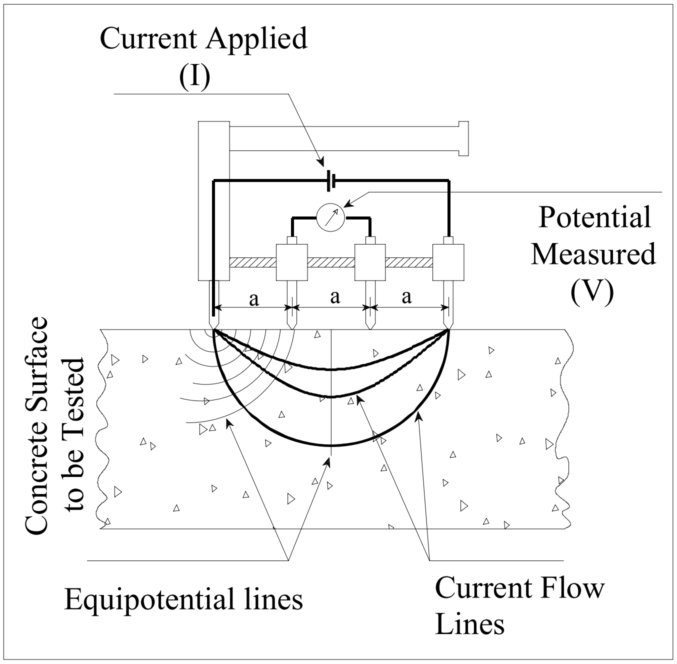


Figure 5. Four-point Wenner Probe Test Setup.

Results from Wenner Probe testing can vary significantly if the degree of saturation or conductivity of the concrete is inconsistent. Techniques to achieve more uniform saturation, such as vacuum saturation or submerging in water overnight, can be performed in the laboratory. However, the laboratory pre-saturation procedure still presents some inconsistencies. The known conductivity of the added solution changes when mixed with the ions (mainly alkali hydroxides) still present in the concrete pores after the drying process (Hooton, Thomas and Stanish 2001). To overcome this problem, Streicher and Alexander (1995) suggested the use of a high conductivity solution, for example 5 M NaCl, to saturate the sample so that the change in conductivity from the ions remaining in the concrete is insignificant.

Use of the Wenner Probe on concrete in the field presents further complications. The test can give misleading results when used on field samples with unknown conductivity pore solution. Therefore, the pore solution must be removed from the sample to determine its resistivity or the sample must be pre-saturated with a known conductivity solution (Hooton, Thomas and Stanish 2001). Moreover, pre-saturation of the concrete requires that the sample be first dried to prevent dilution of the saturation solution. Some *in situ* drying techniques, however, can cause microcracks to form in the pore structure of the concrete, resulting in an increase in diffusivity. Another possible problem with the *in situ* readings is that reinforcing steel can cause a "short circuit" path and give a misleadingly low reading. The readings should be taken at right-angles to the steel rather than along the reinforcing length to minimize this error (Broomfield and Millard 2002). Hooton, Thomas and Stanish (2001) have suggested that because of these problems, the Wenner probe should only be used in the laboratory, on either laboratory-cast specimens or on cores taken from the structure without steel.

The test probe spacing is critical to obtaining accurate measurements of surface resistivity. The Wenner resistivity technique assumes that the material measured is homogeneous (Chini, Muszynski and Hicks 2003). In addition, the electrical resistivity of the concrete is mainly governed by the cement paste microstructure (Whiting, and Mohamad 2003). It depends upon the capillary pore size, pore system complexity and moisture content. Changes in aggregate type, however, can influence the electrical resistivity of concrete. Monfore (1962) measured the electrical resistivity of several aggregates typically used in concrete by themselves (see Table 5). The resistivity of a concrete mixture containing granite aggregate has higher than a mixture containing limestone (Whiting and Mohamad 2003). Moreover, other research (Hughes, Soleit and Brierly 1985) shows that as the aggregate content increases, the electrical resistance of the concrete will also increase. Gowers and Millard (1999) determined that the minimum probe spacing should be 1.5 times the maximum aggregate size, or ¼ the depth of the specimen, to guarantee more accurate readings. Morris, Moreno and Sagües 1996 suggest averaging multiple readings taken with varying internal probe spacings. Another reasonable technique is to average multiple readings in different locations of the concrete surface. In the case of test cylinders, the readings can be made in four locations at 90-degree increments to minimized variability induced by the presence of a single aggregate particle interfering with the readings (Chini, Muszynski and Hicks 2003).

Chini, Muszynski and Hicks (2003) evaluated the possible replacement of the widely used electrical RCP test (AASHTO T277, ASTM C1202) by the simple non-destructive surface resistivity test. The research program correlated results from the two tests from a wide population of more than 500 sample sets. The samples were collected from actual job sites of concrete pours at the state of Florida. The tests were compared over the entire sample population regardless of concrete class or admixture present to evaluate the strength of the relationship between procedures. The two tests showed a strong relationship. The levels of agreement (R^2) values reported were as high as 0.95 for samples tested at 28 days and 0.93 for samples tested at 91 days. Finally, a rating table to aid the interpretation of the surface resistivity results was proposed (see Table 6) based on the previous permeability ranges provided in the standard RCP test (see Table 1).

Table 5. Measured Electrical Resistivities of Typical Aggregates used for Concrete (Monfore 1968)

Type of Aggregate	Resistivity (ohm-cm)
Sandstone	18,000
Limestone	30,000
Marble	290,000
Granite	880,000

Table 6. Apparent Surface Resistivity for 4-inch (102-mm) Diameter by 8-inch (204-mm) Long Concrete Cylinder using a Four-point Wenner Probe with 1.5-inch (38-mm) Probe Spacing. Values for 28 and 91-day Test (Chini, Muszynski and Hicks 2003).

Chloride Ion Permeability	RCP Test Charge (Coulombs)	Surface Resistivity Test	
		28-Day Test (KOhm-cm)	91-Day Test (KOhm-cm)
High	> 4,000	< 12	< 11
Moderate	2,000 - 4,000	12 -21	11 -19
Low	1,000 - 2,000	21 – 37	19 – 37
Very Low	100 - 1,000	37 – 254	37 – 295
Negligible	< 100	> 254	> 295

2.2.7 IMPRESSED CURRENT (FM 5-522)

The steel reinforcement embedded in concrete under normal conditions, adequate concrete cover and in the absence of foreign ions, does not corrode. The abundant amount of calcium hydroxide and relatively small amounts of alkali elements present in the concrete creates a very high alkaline environment (pH greater than 13). At the early age of the concrete, this high alkalinity environment results in the formation of a surface layer of the embedded steel. This tightly adhering passive film limits the access of oxygen and moisture to the metal surface. Therefore, as long as this film is not disturbed, it will keep the steel passive and protected from corrosion (Mindess, Young and Darwin 2002).

Chloride ions have the special ability to destroy the passive oxide film on steel to initiate corrosion damage. Corrosion to the reinforcing steel results in an accumulation of voluminous corrosion products, generating internal stresses and subsequent cracking and spalling of the concrete. Spellman and Stratfull (1973) developed a testing technique to categorize the corrosion protective properties of the reinforced concrete under chloride ion attack. The procedure involved chloride exposure to a freely corroding, partially submerged reinforced specimen. The region near or bellow the water line became anodic due to the chloride penetration and the reinforcing steel, which was in the air, became the cathodic. Therefore, corrosion of the steel in the anodic region was driven by the cathodic portion in the air. The testing procedure presented a major drawback. The duration required to for the experiment to evolve corrosion to cause cracking of a concrete specimen was approximately six to twelve moths for a relatively small concrete cover of approximately 0.75-inch (19-mm).

Following the principles of Spellman and Stratfull (1973) work, an accelerated impressed current laboratory test was developed (Brown and Kessler 1978; Hartt and Brown 1979) to characterize the tendency of embedded metal corrosion to cause cracking of a concrete specimen. The impressed current test involved subjecting a 4-inch (102-mm) diameter by 5.75-inch (146-mm) thick concrete cylinder with a No.4 reinforced bar embedded (see Figure 6) to an external electrical potential to force the chlorides ions to migrate into the specimen. The samples are kept partially submerged during the experiment in 5 percent NaCl solution (see Figure 7). It was established that varying the external electrical potential would increase or decrease the time to failure of the specimens. Therefore, six volts DC was found as an adequate value to complete the test in a reasonable period of time. The current of the specimen is then measured on a daily basis until either the specimen visibly cracked or the current increased significantly (typically 1 mV or more). The test procedure was intended as a method for comparison between different concrete mixtures, concrete protective coatings and rebar claddings and coatings. Therefore, inclusion of test data from “standard” mixture design or “standard” rebar provides a helpful tool for comparison. Longer time for the visible crack to develop and lower measured current (higher resistance) are indicative of improvement over the standard mixture.

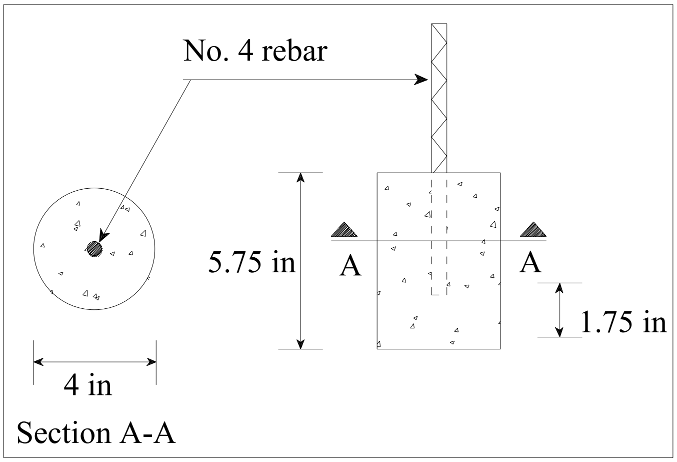


Figure 6. Impressed Current Sample Configuration.

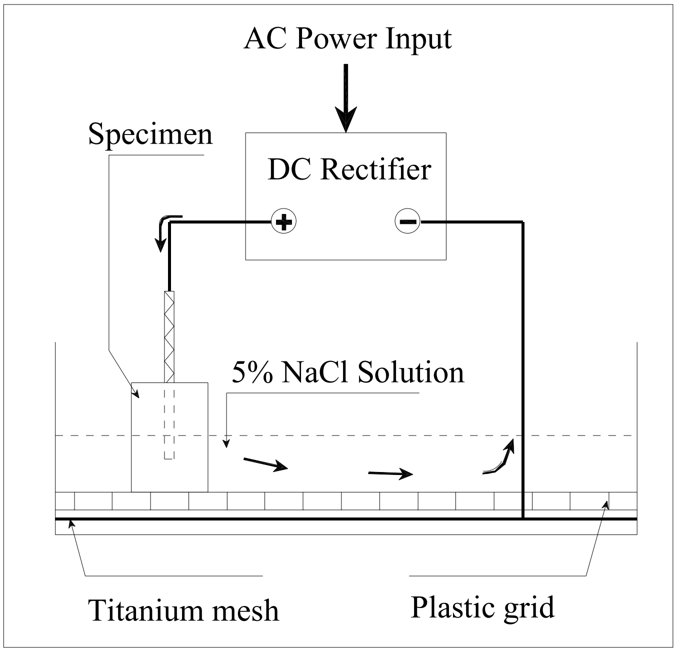


Figure 7. Impressed Current Schematic Test Set-up.

3 CONCRETE MIXTURE DESIGNS AND SAMPLING

3.1 LABORATORY CONCRETE MIXTURES

The primary objective of this research was to compare the RMT procedure to other standard test methods of chloride penetration analysis containing locally available materials in the State of Florida. To ensure that the comparisons were valid, twelve representative mixtures were selected and cast in the laboratory, such that they represented a variety of different concrete qualities and constituents. These concrete mixtures were selected from a range of possibilities, from the most permeable possible designs to less permeable quality mixtures that include pozzolans and a single mixture containing calcium nitrate corrosion inhibitor (see Table 7 and Table 8). The wide permeability range between the selected designs should allow a better point of comparison between RMT and the other tests, under for different conditions.

Table 7. Material Sources for Laboratory Mixtures.

Materials	Source
Portland Cement	CEMEX Type II
Fly-Ash	Boral Materials Technologies Inc. Fly Ash Class F
Classified Fly-Ash	Boral Materials Technologies Inc. Micron^3
Silica Fume	W.R. Grace Force 10,000D
Metakaolin	Burgess Pigment Co. Burgess #30
Slag	Lafarge NewCem-Grade 120
Calcium Nitrite	W.R. GRACE DCI-S
Water	Gainesville, FL
Fine Aggregate	Silica Sand
Coarse Aggregate	Crushed Limestone
Air Entrainer	W.R. Grace Darex
Water Reducer	W.R. Grace WRDA 64
Super Plasticizer	W.R. GRACE Daracem 19

Table 8. Laboratory Mixture Designs.

	Mixture Name											
Materials	**CPR1**	**CPR2**	**CPR3**	**CPR4**	**CPR5**	**CPR6**	**CPR7**	**CPR8**	**CPR9**	**CPR10**	**CPR11**	**CPR12**
Casting Date	9/29/03	10/15/03	10/21/03	10/22/03	10/23/03	1/5/04	1/28/04	1/29/04	2/4/04	2/5/04	2/17/04	3/9/04
W/C	0.49	0.35	0.45	0.28	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Cement (pcy)	564	752	752	648	601.6	661.8	691.8	541.4	676.8	526.4	376	752
Pozzolan 1 (pcy)	-	-	-	Fly-Ash (20%) 180	Fly-Ash (20%) 150.4	Classified Fly-Ash (12%) 90.2	-	Fly-Ash (20%) 150.4	-	Fly-Ash (20%) 150.4	-	-
Pozzolan 2 (pcy)	-	-	-	Silica Fume (8%) 72	-	-	Silica Fume (8%) 60.2	Silica Fume (8%) 60.2	Metakaolin (10%) 75.2	Metakaolin (10%) 75.2	Slag (50%) 376	-
Water (pcy)	276.4	263.2	338.4	252	263.2	263.2	263.2	263.2	263.2	263.2	263.2	229.5
Fine Aggregate (pcy)	1,105	1,080	990	1,000	1,043	1,061	1,058	1,021	1,051	1,037	1,053	1,030
Coarse Aggregate (pcy)	1,841	1,750	1,647	1,670	1,750	1,750	1,750	1,750	1,750	1,729	1,750	1,703
Calcium Nitrate (oz)	-	-	-	-	-	-	-	-	-	-	-	576
Air Entrainer (oz)	3.0	4.0	4.0	6.8	5.6	5.6	5.6	5.6	5.6	5.6	5.6	7.5
Water Reducer (oz)	18.3	24.4	24.4	29.3	24.4	24.4	24.4	24.4	24.4	24.4	24.4	24.4
Super Plasticizer (oz)	20.2	29.7	17.7	180	37.6	45.1	37.6	45.1	90.2	136.9	33.8	33.8

The mixtures were prepared under controlled environmental conditions, with a constant air temperature. The size of the concrete batch for each mixture was six cubic feet (0.17 cubic meters). This volume of concrete included the specimens, concrete for quality control testing, and several extra samples. The quality control procedures executed during mixing and casting of the test samples were:

- Standard Test Method for Slump of Hydraulic Cement Concrete (ASTM C 143).
- Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method (ASTM C 173).
- Standard Test Method for Temperature of Freshly Mixed Portland Cement Concrete (ASTM C 1064).
- Standard Test Method for Density (Unit Weight) of Freshly Mixed Concrete (ASTM C 138).

The standard process for casting concrete cylinders proposed by the AASHTO T23 method was followed (see Table 9). An external vibration device, also known as vibrating table was used to ensure complete compaction of the specimens. The 4-inch (102-mm) diameter cylinders were cast and vibrated in two layers as is shown in Table 9. The vibration period for each mixture was determined by visual inspection of the first set of samples vibrated. The samples were vibrated until the larger air bubbles ceased breaking through the top of surface but before visible segregation occurred. It was generally between 15-seconds to 30-seconds for each inserted layer. After the samples were cast in their respective molds and the top exposed surface finished with the help of a trowel, they were left approximately 24-hours for atmospheric curing. During this period, the exposed surfaces of samples were covered with plastic bags (see Figure 8) to minimize evaporation of the water in the surface of the concrete. Finally, the samples were de-molded and placed in their particular curing environment until their testing date.

Table 9. Standard Method for Casting and Vibrating Concrete Cylinders (AASHTO T23).

Cylinder Diameter (in)	Number of Layers	Number of Vibrator Insertions per Layer	Approximate Depth of Layer
4	2	1	½ depth of specimen
6	2	2	½ depth of specimen
9	2	4	½ depth of specimen

Figure 8. Air Curing of Cast Concrete Specimens.

3.2 *FIELD CONCRETE MIXTURES*

In addition to the laboratory concrete mixtures, seven field mixtures obtained from FDOT construction projects around the state were collected. The mixtures were chosen to represent a wide range of concrete permeabilities through the use of different constituents. From the FDOT concrete specification (see Table 10), Class II concrete was chosen as the lower bound of the range as most permeable, and Class V and VI as the least permeable (see Table 11 and Table 12). These mixtures also represent the typical concretes used in structural members such as bridge concrete barriers, prestressed concrete beams and piles that are constantly exposed to chloride attacks.

The State of Florida is divided by the FDOT into seven geographic regions (see Figure 11). In order to attain a balanced group of samples that reflected local materials of the state, specimens from three districts were collected. Samples from District 3 (North Florida), District 2 (Central Florida) and District 4 (South Florida) were selected (see Figure 11 and Table 13). The concrete batches for the specimens were supplied directly from mixer trucks to several wheel barrows at the job site or at the ready mix plant (see Figure 9). The volume of concrete supplied was enough for the casting of the specimens, quality control testing, and several extra samples. The same quality control testing and standard casting procedures for the laboratory mixtures were followed in the field.

Figure 9. Casting of Field Mixture Specimens.

After the samples were cast in their respective molds, they were left approximately 24-hours for atmospheric air curing with the exposed surfaces covered by plastic bags to prevent evaporation of water from the concrete. Afterward, they were de-molded and submerged in water tanks, so that their treatment prior to arriving at the laboratory is controlled curing conditions was as uniform as possible (see Figure 10). The high temperature of the water tanks induced by Florida's hot weather was controlled by the addition of several bags of ice.

Figure 10. Field Samples Curing during transport to Laboratory.

Table 10. Specified Compressive Strength of FDOT Concrete Classes.

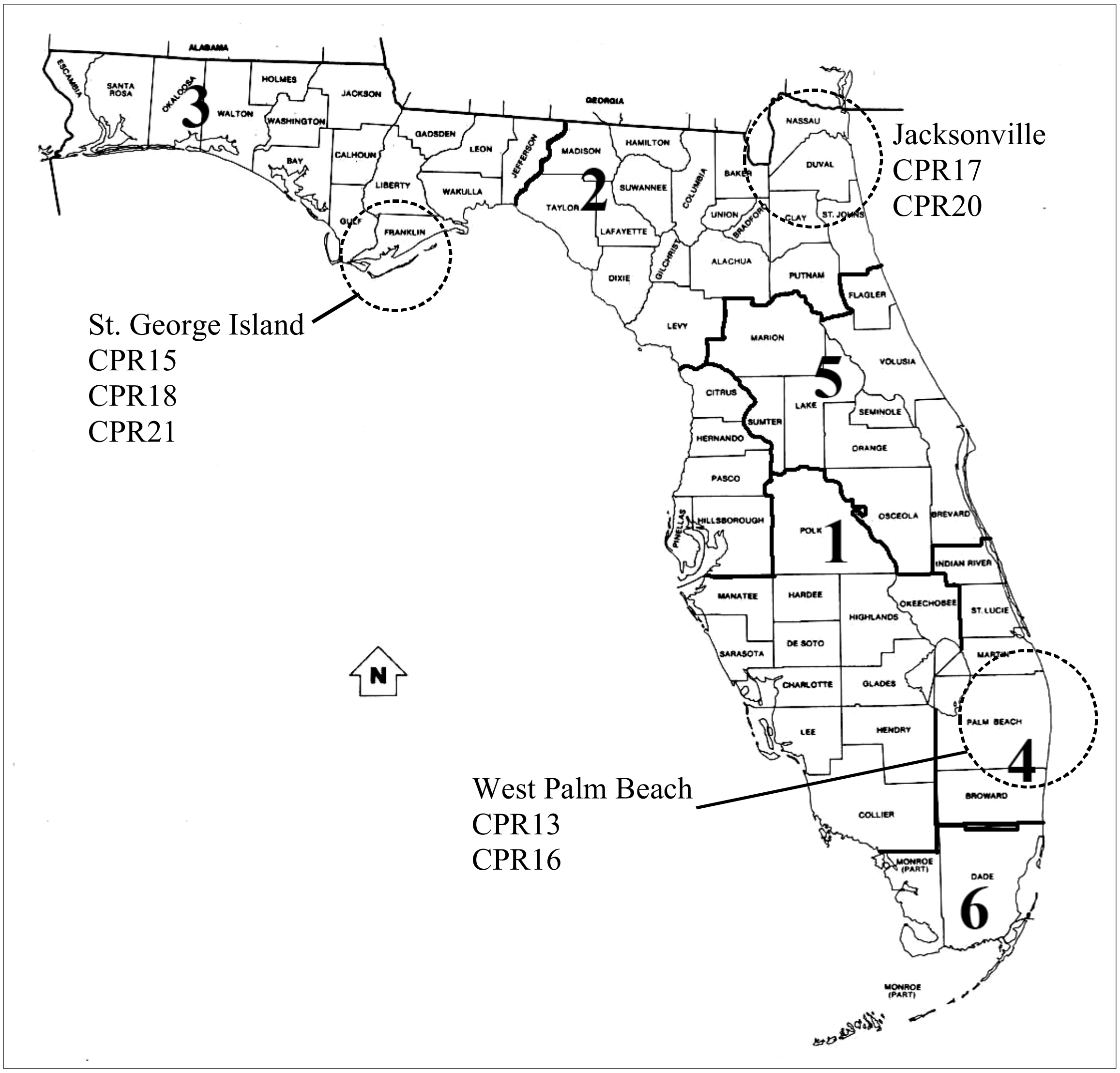
FDOT Concrete Classes	**Design Compressive Strength (psi)**
Class I	3,000
Class I Special	3,000
Class II	3,400
Class II Bridge Deck	4,500
Class III	5,000
Class III Seal	3,000
Class IV	5,500
Class IV Drill Shaft	4,000
Class V	6,500
Class V Special	6,000
Class VI	8,500

Table 11. Field Mixture Designs.

Materials	Mixture Name, FDOT Concrete Classes and Geographic Location						
	CPR13	**CPR15**	**CPR16**	**CPR17**	**CPR18**	**CPR20**	**CPR21**
	Class II	Class II	Class V	Class V	Class V	Class VI	Class VI
	South FL	North FL	South FL	Central FL	North FL	Central FL	North FL
Casting Date	8/11/2003	7/11/2003	8/12/2003	7/18/2003	7/9/2003	7/17/2003	7/10/2003
W/C	0.45	0.29	0.33	0.34	0.30	0.28	0.29
Cement(pcy)	569.7	450	657.4	686	673	800	770
Pozzolan 1 (pcy)	-	Fly-Ash (20%) 115	Fly-Ash (18%) 150	Fly-Ash (18%) 154	Fly-Ash (20%) 169	Fly-Ash (20%) 200	Fly-Ash (18%) 165
Water (pcy)	254.5	162.3	269.7	288	251.9	280	267.5
Fine Aggregate (pcy)	1,434	1,137	1,048	935	973.5	868	727.5
Coarse Aggregate (pcy)	1,655	1,918	1,724	1,720	1,914	1,650	1,918
Air Entrainer (oz)	0.3	2.0	1.0	5.0	4.0	2.0	5.0
Water Reducer (oz)	45.6	22	8.0	17	40	16	47
Super Plasticizer (oz)	-	-	70.0	55.0	110	52	110

Table 12. Field Mixture Material Sources.

Materials	**Source**						
	CPR13	**CPR15**	**CPR16**	**CPR17**	**CPR18**	**CPR20**	**CPR21**
Portland Cement	RINKER Miami Type II	Southdown Brooksville Type II	RINKER Monjos Type I	PENNSUCO Type II	CEMEX Type II	PENNSUCO Type II	CEMEX Type II
Fly-Ash	-	BORAL Plant Daniel Class F	BORAL BOWEN Class F	ISG Fernandine Beach, FL Class F	BORAL Plant Daniel Class F	ISG Fernandine Beach, FL Class F	BORAL Plant Daniel Class F
Water	Miami, FL	St. George Island, FL	West Palm Beach, FL	Jacksonville, FL	St. George Island, FL	Jacksonville, FL	St. George Island, FL
Fine Aggregate	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand	Silica Sand
Coarse Aggregate	Crushed Limestone	Crushed Granite	Crushed Limestone	Crushed Limestone	Crushed Granite	Crushed Limestone	Crushed Granite
Air Entrainer	W.R. GRACE DAREX	Master Builders MBAE-90	Master Builders MBAE-90	Master Builders MBVR-S	Master Builders MBAE-90	Master Builders MBVR-S	Master Builders MBAE-90
Water Reducer	W.R. GRACE WRDA 60	Master Builders POZZ 300R	Master Builders POZZ 961R	Master Builders POZZ 100XR	Master Builders POZZ 300R	Master Builders POZZ 100XR	Master Builders POZZ 300R
Super Plasticizer	-	-	Master Builders POZZ 400N	Master Builders RHEO 1,000	Master Builders RHEO 1,000	Master Builders 3,000FC	Master Builders RHEO 1,000



Jacksonville
CPR17
CPR20

St. George Island
CPR15
CPR18
CPR21

West Palm Beach
CPR13
CPR16

Figure 11. FDOT District Map with Field Mixture Locations.

Table 13. Facilities That Provided Field Mixtures.

FDOT District	Mixture Name	Concrete Class	Location of the Concrete Casting	Location and Contact Information of the Concrete Supplier Plant
DISTRICT 4	CPR13	Class II	Interstate I-95 at West Palm Beach, FL.	RINKER MATERIALS CORP. 1501 Belvedere Road. Belle Glade West Palm Beach, FL 32406 Phone: (561) 833-5555 FDOT Plant No. 93-104
	CPR16	Class V	At the Plant	S. EASTERN PRESTRESS CONCRETE INC. West Palm Beach, FL 33416 P.O. BOX 15043 Phone: (561) 793-1177 FDOT Plant No. 93-101
DISTRICT 2	CPR17	Class V	At the Plant	GATE CONCRETE PRODUCTS 402 Hecksher Drive Jacksonville, FL 32226 Phone: (904) 757-0860 FDOT Plant No. 72-055
	CPR20	Class VI		
DISTRICT 3	CPR15	Class II	At the Plant	COUCH CONCRETE 60 Otterslide Rd. Eastpoint, FL 32328 Phone: (850) 670-5512 FDOT Plant No. 49-479
	CPR18	Class V	St. George Island Bridge Construction Site	
	CPR21	Class VI		

4 TEST PROCEDURES

A total of 1444 samples from 19 separate mixtures were cast for testing. The concrete mixtures were divided into two groups. Twelve were mixed and formed at the FDOT State Materials Office (SMO) in Gainesville (Table 14).

The remaining 7 mixtures were obtained at various field sites around the state and brought back to the SMO for storage and eventual testing (see Table 15). The samples were primarily 4-inch (102-mm) diameter by 8-inch (204-mm) long cylinders with some 4-inch (102-mm) diameter by 5.75-inch (146-mm) long cylinders for the impressed current (FM 5-522) test and 3-inch (76-mm) thick by 12-inch (305-mm) square slabs for the 90-day salt ponding testing (AASHTO T259).

Table 14. Concrete Permeability Research Sample Matrix for Laboratory Mixtures.

		Electrical Permeability Tests				Diffusion Tests		
Test Name	**Strength**	**RCP**	**Surface Resistivity**	**Impressed Current**	**RMT**	**Diffusion**	**Bulk Diffusion**	**Extra Cylinders**
Test Method	**ASTM C39**	**AASHTO T277**	**SR**	**FM5-522**	**NTBuild 492**	**AASHTO T259**	**NTBuild 443**	
Sample Size	**4”x8” Cylinder**	**4”x8” Cylinder**	**4”x8” Cylinder**	**4”x5.75” Cylinder**	**4”x8” Cylinder**	**12”x12”x 3” Slabs**	**4”x8” Cylinder**	**4”x8” Cylinder**
Mixture Name	**Total Number of Samples per Test**							
CPR1	18	18	6	3	18	3	3	7
CPR2	18	18	6	3	18	3	3	7
CPR3	18	18	6	3	18	3	3	7
CPR4	18	18	6	3	18	3	3	7
CPR5	18	18	6	3	18	3	3	7
CPR6	18	18	6	3	18	3	3	7
CPR7	18	18	6	3	18	3	3	7
CPR8	18	18	6	3	18	3	3	7
CPR9	18	18	6	3	18	3	3	7
CPR10	18	18	6	3	18	3	3	7
CPR11	18	18	6	3	18	3	3	7
CPR12	18	18	6	3	18	3	3	7
Subtotal	**216**	**216**	**72**	**36**	**216**	**36**	**36**	**84**
Total	**912**							

Table 15. Concrete Permeability Research Sample Matrix for Field Mixtures.

		Electrical Permeability Tests				Diffusion Tests		
Test Name	**Strength**	**RCP**	**Surface Resistivity**	**Impressed Current**	**RMT**	**Diffusion**	**Bulk Diffusion**	**Extra Cylinders**
Test Method	**ASTM C39**	**AASHTO T277**	**SR**	**FM5-522**	**NTBuild 492**	**AASHTO T259**	**NTBuild 443**	
Sample Size	**4”x8” Cylinder**	**4”x8” Cylinder**	**4”x8” Cylinder**	**4”x5.75” Cylinder**	**4”x8” Cylinder**	**12”x12”x 3” Slabs**	**4”x8” Cylinder**	**4”x8” Cylinder**
Mixture Name	**Total Number of Sample per Test**							
CPR13	18	18	6	3	18	3	3	7
CPR15	18	18	6	3	18	3	3	7
CPR16	18	18	6	3	18	3	3	7
CPR17	18	18	6	3	18	3	3	7
CPR18	18	18	6	3	18	3	3	7
CPR20	18	18	6	3	18	3	3	7
CPR21	18	18	6	3	18	3	3	7
Subtotal	**126**	**126**	**42**	**21**	**126**	**21**	**21**	**49**
Total	**532**							

4.1 CHLORIDE ION CONTENT ANALYSIS

Chloride ions could be present in concrete in two forms, soluble chlorides in the concrete pore water and chemically bounded chlorides. There are several laboratory methods to estimate these amounts of chloride in the concrete structure. The FDOT standardized test method (FM 5-516) to determine low-levels of chloride in concrete and raw materials was selected for the analysis. This wet chemical analysis method also known as acid-soluble method determines the sum of all chemically bound and free chlorides ions from powdered concrete samples.

4.2 DIFFUSION TESTS

4.2.1 90-DAY SALT PONDING TEST

The 90-day Salt Ponding test procedure was conducted in accordance with AASHTO T259 using three concrete slabs measuring 3-inch (76-mm) thick and 12-inch (305-mm) square for each mixture. The slabs were moist cured in a room with a sustained 100% humidity for 14 days and kept for an additional 28 days in a drying room with a 50 percent relative humidity environment. A plastic dam with approximately 0.75-inch (19-mm) high by 0.5-inch (13-mm) dimension was affixed to the non-finished face of the slab and a 3 percent NaCl solution was ponded into the dam, leaving the bottom face exposed to the drying environment (see Figure 1 and Figure 12). The slabs were subjected to continuous ponding to a depth of approximately 0.5-inch (13-mm) of solution for the entire exposure period.

Figure 12. Ninety-day Salt Ponding Test Set-Up used in CPR

The standard test procedure calls for a chloride ion analysis for depth of penetration after an exposure period of 90 days. Previous research conducted at SMO indicated that even 182 days was insufficient time for chlorides to penetrate concrete mixtures of similar quality. Hence, the samples were allowed to run for 364 days before conducting chloride sampling. Chlorides were sampled at 0.25-inch (6.5-mm) increments rather than the 0.5-inch (13-mm) increments suggested by the standard procedure. This gave a better distribution of chloride concentration with depth.

4.2.2 BULK DIFFUSION TEST

The Bulk Diffusion Test was conducted using the NT BUILD 443 (NT BUILD 443 1995) test procedure. Samples were 4-inch (102-mm) diameter by 8-inch (204-mm) long, with three samples cast for each mixture. The samples were kept in a moist room with a sustained 100% humidity for 28 days, removed from the moist conditions, and sliced on a water-cooled diamond saw into two halves (see Figure 21.a). The cut specimens were immersed in a saturated $Ca(OH)_2$ solution in an environment with an average temperature of 73°F (23°C). The samples were weighed daily in a surface-dry condition until their mass did not change by more than 0.1 percent. The specimens were then sealed with Sikadur 32 Hi-Mod epoxy (on all surfaces except the saw-cut face) and left to cure for 24-hours. The sealed samples were then returned to the $Ca(OH)_2$ tanks to repeat the above saturation process by weight control. The samples were then immersed under surface-dry conditions in salt solution (16.5 percent of sodium chloride solution mixed with deionized water) in tanks with tight closing lids (see Figure 2, Figure 13). The tanks were shaken once a week and the NaCl solution was changed every 5 weeks. The original procedure called for at least 35 days of exposure before the chloride penetration analysis was to be conducted. Moreover, it suggests to sample between 0.04-inch to 0.08-inch (1-mm to 2-mm) increments by powder grinding the profiles for this exposure time and type of high quality concrete. With the equipment available for the use on the project, an exposure of 35 days is insufficient to achieve a measurable chloride profile. A coarser chloride sampling evaluation was implemented; 0.25-inch (6.5-mm) increments were tested on 364 days old samples.

Figure 13. Bulk Diffusion Saline Solution Exposure.

4.3 ELECTRICAL CONDUCTIVITY TESTS

4.3.1 RAPID CHLORIDE PERMEABILITY TEST (RCP)

The RCP test was conducted in conformance with AASHTO T277 and ASTM C1202. The specimen dimensions were 4-inch (102-mm) diameter by 8-inch (204-mm) long. All samples were kept in a moist room with a sustained 100% humidity until testing day. RCP tests were conducted at ages of 14, 28, 56, 91, 182 and 364 days, with three samples tested at each age.

The procedure calls for two days of specimen preparation. On the first day, the samples were removed from the moist room to be cut on a water-cooled diamond saw. A ¼-inch (6.4-mm) slice was first removed to dress the top edge of the sample (Figure 14), and then the 2-inch (51-mm) thick sample required for the test was sliced (Figure 15). The sides of the specimens were roughened (Figure 16) followed by application of Sikadur 32 Hi-Mod epoxy to seal the specimen (Figure 17).

Figure 14. RCP test top surface removal of the sample preparation procedure.

Figure 15. Cutting of the 2-inch Sample for the RCP Test.

The second day of preparation began with the desiccation process to water-saturate the samples. The specimens were placed in a desiccation chamber connected to a vacuum pump capable of maintaining a pressure of less than 1 mm Hg (133 Pa). The vacuum was maintained for three hours to remove the pore solution from the samples (see Figure 18). The container was then filled with boiled de-aerated water until the samples were totally submerged and the pump was left running for an additional hour (see Figure 19). The desiccation chamber was return to atmospheric pressure and the samples were left submerged for 18 hours, plus or minus 2 hours.

Figure 16. Preconditioning RCP Sample Surfaces to Receive Epoxy.

Figure 17. RCP Sample Sealed with Epoxy.

After the samples were removed from the desiccation chamber, each sample was placed into their acrylic cells and sealed with silicone (Figure 3 and Figure 20). The upper surface of the specimen was left in contact with the 3.0 percent NaCl solution (this side of the cell was connected to the negative terminal of the power supply) and the bottom face was exposed to the 0.3 N NaOH solution (this side of the cell was connected to the positive terminal of the power supply). The test was left running for 6 hours with a constant 60-volt potential applied to the cell.

Figure 18. RCP Reduction of Absolute Pressure for Sample Desiccation.

A data logging system recorded the temperature of the anolyte solution, charge passed, and current every 5 minutes. Furthermore, it calculated the cumulative charge passed during the test in coulombs by determining the area under the curve of current (amperes) versus time (seconds). The three total readings from each sample were averaged to obtain a representative final result for the specimens set.

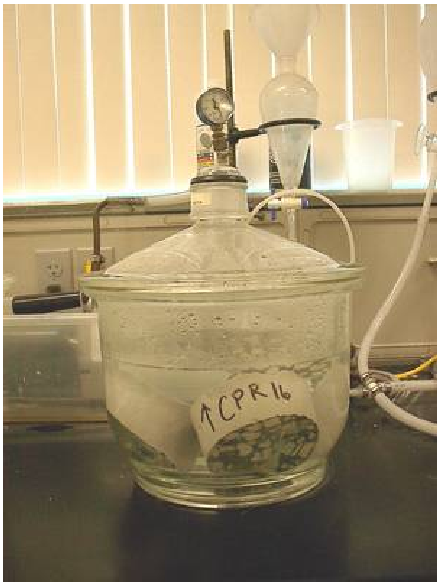


Figure 19. RCP Sample Desiccation.

Figure 20. RCP Test Set-up.

4.3.2 RAPID MIGRATION TEST (RMT)

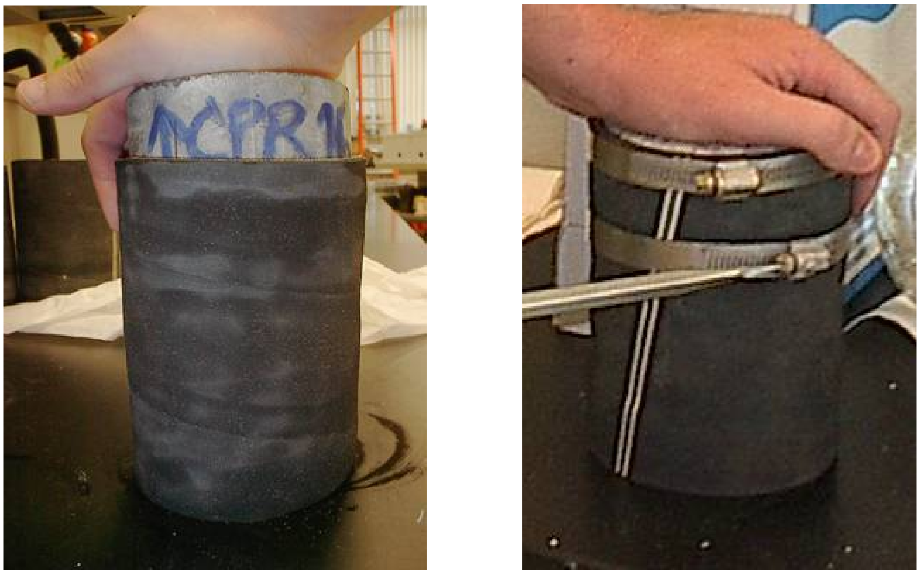
The rapid migration test (RMT) is conducted in a similar manner as that of the RCP test in which an electrical potential is applied to force chlorides through the concrete. A "migration coefficient" is calculated then using a measured depth of chloride penetration. Consequently, the most important single parameter to calculate RMT diffusion coefficient is the depth of chloride penetration. The RMT was conducted in accordance with NordTest NTBuild 492, including the modifications proposed by Hooton, Thomas and Stanish (2001). The changes to the standardized procedure included using a different voltage than specified and adjusting the test duration based on the current measured at the start of the test (see Table 2 and Table 3). For each mixture a total of 19 concrete cylinders 4-inch (102-mm) diameter by 8-inch (51-mm) long were tested. The cylinders were kept in a moist room with a sustained 100% humidity until the testing day. The procedure was conducted at 14, 28, 56, 91, 182 and 364 days using three specimens per age. The test calls for a day of preparation. Specimens were removed from the moist room and cut on a water-cooled diamond saw. They were cut first into two halves with a 2-inch (51-mm) thick sample being cut from each of the two halves (see Figure 21). The side of the sample that was nearer to the first cut (middle surface) was the face to be exposed to the chloride solution (catholyte).

The samples were then subjected to a saturated desiccation procedure similar to the RCP test (see Figure 19). The only difference between the procedures is the liquid used for saturation. The RMT calls for a saturated $Ca(OH)_2$ solution (dissolved in boiled de-aerated water).

After the samples were removed from the desiccation chamber, they were fitted into a rubber sleeve and secured with two stainless steel clamps to prevent possible leaks (see Figure 22). The rubber sleeve containing the sample was positioned on a plastic support and the cathode and anode stainless steel plates were positioned (see Figure 4 and Figure 23). The upper part of the sleeve was filled with a 0.3 N NaOH (1.2% NaOH) anode solution and the complete set-up was immersed into a plastic container filled with the catholyte solution of 10 percent NaCl. The cathode plate connector was connected to the negative terminal and the anode to the positive terminal of the power supply (see Figure 4).

(a) *(b)*

Figure 21. Cutting RMT samples. a) RMT sample cut into two halves, b) Cutting of the 2-inch RMT sample.



(a) *(b)*

Figure 22. RMT Sample Preparation. a) Sample be placed in the rubber sleeve, b) Securing the sample with stainless steel clamps.

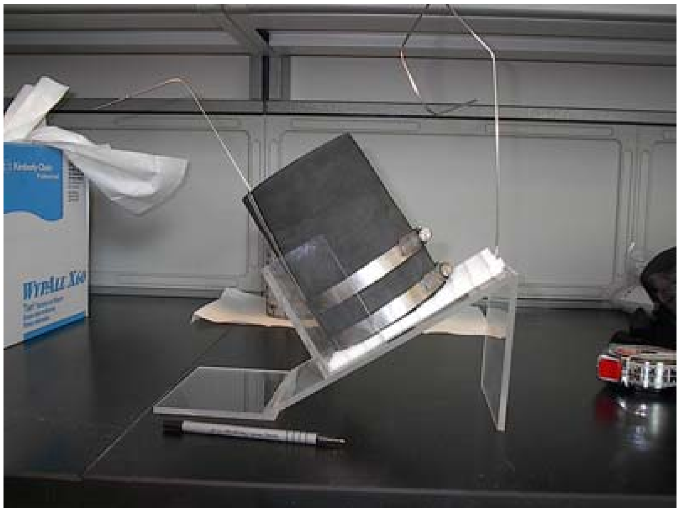


Figure 23. RMT Test Set-up shown prior to being immersed in the catholyte solution.

The power supply was preset to 60-volts and the initial current through each specimen was recorded. The test voltage was then adjusted based on the initial current reading (see Table 3) and left running for 18 hours. A data logger system similar to the RCP equipment read temperature of the anolyte solution, charge passed, and current every 5 minutes.

After the monitoring process of 18 hours was completed, the RMT set-up was disassembled and the concrete samples were removed. The specimens were rinsed with tap water and the excess solution was wiped off the surfaces. The standardized method recommends a colorimetric procedure for measuring the depth chloride infiltration. The accuracy and sensibility of the colorimetric procedure has been questioned by several studies (Andrade et al. 1999; Meck and Sirivivatnanon 2003). Therefore at the beginning of the project, a different analysis approach was chosen. RMT specimens were profiled at varying depths to obtain their respective chloride content in accordance with the FDOT standard test method FM 5-516. Chloride content for ¼-inch (6.4-mm) progressive slices was determined for an average of three samples per mixture (see Figure 24). These slices were pulverized and kept inside plastic bags until the chloride content testing was executed. A chloride profile with a maximum of eight readings for each sample could be obtained. Moreover, to validate the standard proposed colorimetric method, a comparison was made with the results obtained by profiling test method FM 5-516. It was decided that the remainder of the specimens would be additionally tested using the colorimetric approach suggested in the test procedure. Therefore, these set of samples were evaluated by applying the two methods to the same sample. The samples were split as shown on Figure 25. Chloride content was measured on one half with FM 5-516 and the silver nitrate solution spray was used on the other half (see Figure 28). Table 16 shows the mixtures and ages at which each respective method was used.

Table 16. Test Method Used for Determining RMT Depth of Penetration by Testing Age.

Mixture Name	**RMT Testing Age (Days)**					
	14	**28**	**56**	**91**	**182**	**364**
CPR1	C	C	C	C	P	C&P
CPR2	C	C	C	C	C&P	C&P
CPR3	C	C	C	C&P	C&P	C&P
CPR4	C	C	C	P	P	P
CPR5	C	C	C	C&P	C&P	C&P
CPR6	C&P	C&P	C&P	C&P	C&P	C&P
CPR7	C&P	C&P	C&P	C&P	C&P	C&P
CPR8	C&P	C&P	C&P	C&P	C&P	C&P
CPR9	C&P	C&P	C&P	C&P	C&P	C&P
CPR10	C&P	C&P	C&P	C&P	C&P	C&P
CPR11	C&P	C&P	C&P	C&P	C&P	C&P
CPR12	C&P	C&P	C&P	C&P	C&P	C&P
CPR13	C	C	C	C	C&P	C&P
CPR15	C	C	C	C	C	C&P
CPR16	C	C	C	C	C&P	C&P
CPR17	C	C	C	C	C&P	C&P
CPR18	C	C	C	C	C&P	C&P
CPR20	C	C	C	C	C&P	C&P
CPR21	C	C	C	C	C	C&P

C: Chloride Profile Testing.
P: Silver Nitrate Solution Penetration Measurement (Colorimetric).

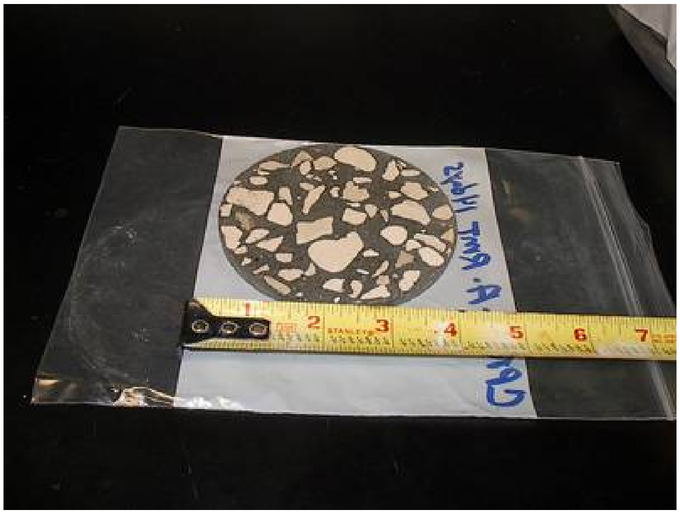


Figure 24. RMT ¼-in concrete slice for chloride content analysis.

For the silver nitrate method, the split section more nearly perpendicular to the end surfaces was selected for the depth of penetration analysis. The freshly split section was sprayed with a 0.1M silver nitrate solution creating a chemical reaction where the chlorides present in the concrete reacted and produced a white silver precipitation on the surface clearly visible (see

Figure 26). A brownish color was created on the surface where the silver nitrate solution, in the absence of chlorides, reacted instead with the hydroxides present in the concrete (see Figure 26).

The location of the line between the two colors was measured using the help of a slide caliper. A total of eight evenly spaced penetration depth readings were taken starting 0.4 inch (10 mm) away from the edges of the specimen to avoid the possible effect due to a non-homogeneous degree of saturation or a possible leakage during the exposure procedure (see Figure 27). The readings were averaged to obtain the relative depth of chloride penetration for each specimen.

(a) *(b)*

Figure 25. Silver Nitrate Solution Spray method Sample Preparation. a) Specimen axially being split, (b) Faces of split sample.

Figure 26. Split Surface of the Specimen Sprayed with the Silver Nitrate Solution.

Figure 27. Chloride Penetration Measurement using the Silver Nitrate Solution Method.

Figure 28. Slicing Samples for Comparison between FM 5-516 and Silver Nitrate Solution Spray Chloride Methods.

4.3.3 SURFACE RESISTIVITY TEST

The surface resistivity tests were conducted conforming to Florida Method of Test designation FM 5-578. The surface resistivity was measured on 4-inch (102-mm) diameter by 8-inch (204-mm) long concrete cylinders. To evaluate the effect of curing, two sets of three samples each were tested. The first set was kept in a moist room with a sustained 100% humidity, and the other in saturated $Ca(OH)_2$ solution (dissolved in tap water) tanks. Due to its nondestructive test nature, the test was performed to a wider amount of ages than the other electrical tests. For the purpose of this project, the samples were tested at 14, 28, 56, 91, 182, 364, 454 and 544 days. Additionally, these samples are being monitoring until no further changes in the surface resistivity reading is observed as part of another research project.

Commercial four-probe Wenner array equipment was utilized for resistivity measurements. The model used had wooden plugs in the end of the probes that were pre-wetted with a contact medium to improve the electrical transfer with the concrete surface (see Figure 29). The inter-probe spacing was set to 1.5-inch (38-mm) for all measurements.

On the day of testing the samples were removed from their curing environment and the readings were taken under surface wet condition. Readings were then taken with the instrument placed such that the probes were aligned with the cylinder axis. Four separate readings were taken around the circumference of the cylinder at 90-degrees increments (0^o, 90^o, 180^o and 270^o). This process was repeated once again, in order to get a total of eight readings that were then averaged. This minimized possible interference due to the presence of a single aggregate particle obstructing the readings (Chini, Muszynski and Hicks 2003).

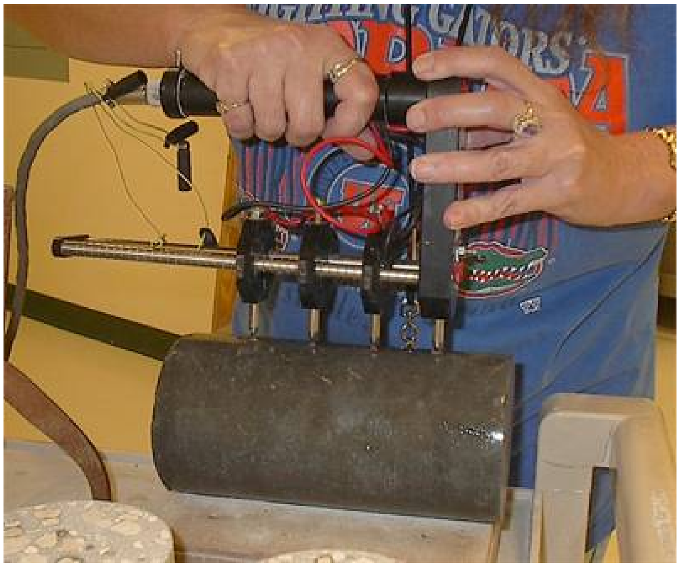


Figure 29. Surface Resistivity Measurements.

4.3.4 IMPRESSED CURRENT

Impressed Current tests were conducted conforming to Florida Method of Test designation FM 5-522. The samples tested were a set of three 4-inch (102-mm) diameter by 5.75-inch (146-mm) thick concrete cylinders with a No.4 reinforced bar positioned as shown in Figure 6. The cylinders were kept in a moist room with a sustained 100% relative humidity for 28 days. They were then removed and placed in a 5 percent NaCl solution tank. The level of solution was kept 3-inch (75-mm) above the bottom of the specimens for an additional 28 days.

At the end of the 28 days of preconditioning, the exposed bar was connected to the positive output terminal of a half-wave rectifier. The negative terminal of the power supply was connected to a titanium anode mesh on the bottom of the tank beneath a plastic grid (see Figure 7 and Figure 30).

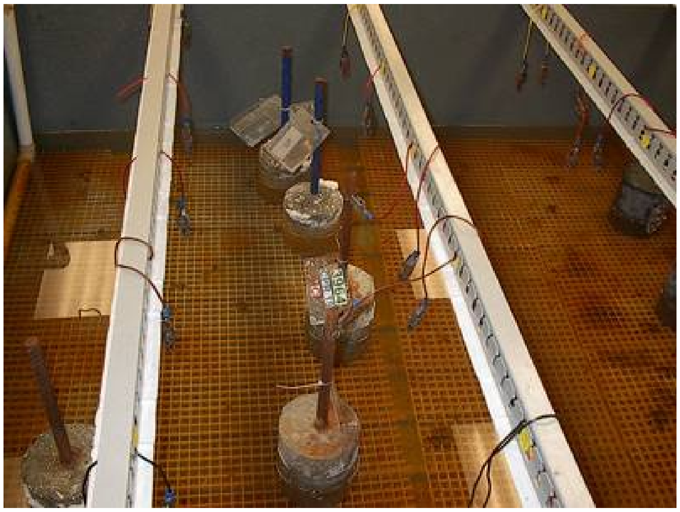


Figure 30. Impressed Current Test Set-up.

The DC power supply was adjusted to 6-volts and the current to each specimen was measured on a daily basis. The measurements were made until either the specimen visibly cracked (see Figure 31) or the current increased significantly (typically 1 mV or more) (see Figure 32). Finally, the daily resistance is calculated by dividing the constant applied voltage by the average of daily current until the time to failure of the specimen.

Figure 31. Visible Crack in Impressed Current Specimen.

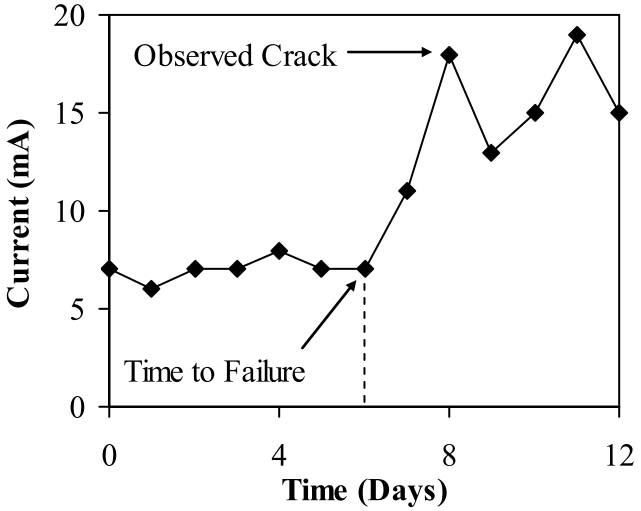


Figure 32. Typical Example of a Daily Recorded Data for an Impressed Current Specimen.

5 RESULTS AND DISCUSSION

5.1 FRESH CONCRETE PROPERTIES AND COMPRESSIVE STRENGTHS

Several quality control procedures were executed during mixing and casting of the test samples for the laboratory and field mixtures. The results obtained from the standard testing procedures for slump (ASTM C 143), air content (ASTM C 173), concrete temperature (ASTM C 1064), air temperature and unit weight of the concrete (ASTM C 138) are included in Table 17.

Table 17. Fresh Concrete Properties.

Mixture Name	Slump (in)	Air Content (%)	Concrete Temperature (°F)	Air Temperature (°F)	Unit Weight (pcf)
CPR1	7.5	3.5	76	72	140.62
CPR2	3	2	79	72	144.62
CPR3	9.75	2.5	80	75	140.40
CPR4	9	3	81	75	142.32
CPR5	2.25	1.5	80	72	144.32
CPR6	6	4.5	80	73	140.52
CPR7	3	2.5	76	72	143.72
CPR8	4	4.5	78	70	139.72
CPR9	5.5	4.5	76	78	145.22
CPR10	8	1.25	80	80	144.02
CPR11	6	2	74	72	142.82
CPR12	9	6	76	72	140.49
CPR13	0.5	4	94	81	140.49
CPR15	3	1.5	92	96	148.64
CPR16	7	3.5	88	98	145.01
CPR17	7	2	90	89	143.08
CPR18	6.5	1.7	96	99	148.77
CPR20	7.75	2.8	98	93	142.16
CPR21	5.5	2	93	96	147.39

The compressive strength of each mixture was evaluated in accordance with ASTM C39. Though compressive strength is not a concrete permeability indicator, it represents a helpful tool for checking the design compressive strength. Compressive strengths were tested after 14, 28, 56, 91,182 and 364 days of continuous moist curing for all the concrete mixtures. Detailed results are given in APPENDIX A. Maximum values of strength were achieved in mixtures with the lowest water-cement ratios. The effect on the mixtures by the addition of fly ash resulted in a slower gain of strength during the early ages of hydration. During the first 56 days after casting, compressive strength of fly ash mixture was significantly less than those of the control mixture (see Figure 33). This lower early strength development is due to the low reactivity of the mineral admixture fly ash (Mindess,Young and Darwin 2002). Strength tests conducted between 56 and 180 days showed that the fly ash mixtures gained a compressive strength comparably equal to those of the control mixture. Finally at 364 days after casting, the fly ash mixtures developed a higher compressive strength exceeding those of the control mixture.

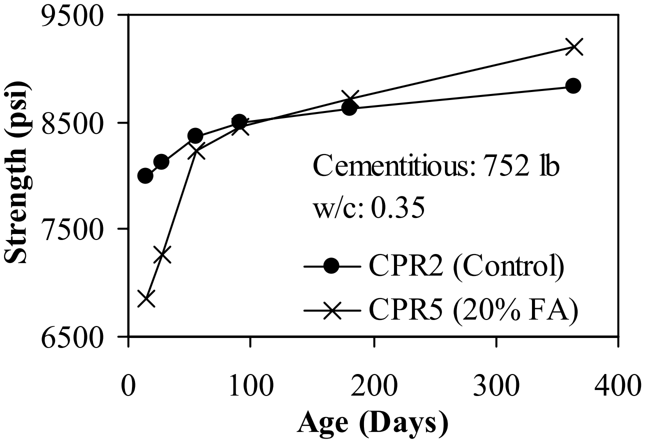


Figure 33. Comparative Compressive Strength Development of Laboratory Control Mixture (CPR2) and Laboratory Mixture Containing Fly Ash (CPR5).

The effect on the mixtures by the addition of the highly reactive pozzolan silica fume contributed to the early development of compressive strength. During the first 14 days after casting, compressive strength of silica fume mixtures was less than those of the control mixture (see Figure 34). On the other hand, strength tests conducted between 28 and 182 days showed that the silica fume mixtures had higher compressive strengths than those of the control mixture. Finally at 364 days after casting, the effect of silica fume was stabilized and the compressive strength was comparably equal to those of the control mixture.

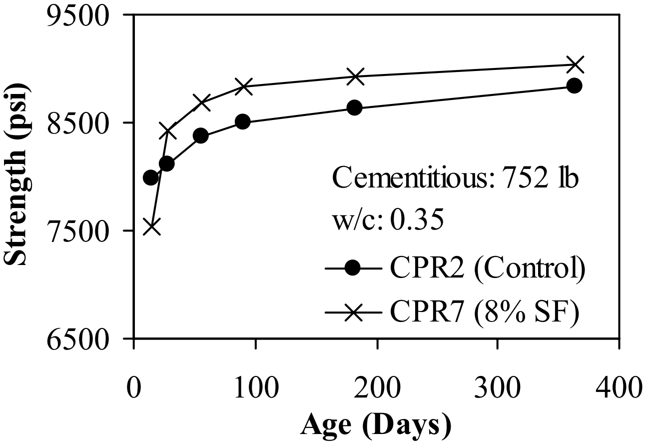


Figure 34. Comparative Compressive Strength Development of Laboratory Control Mixture (CPR2) and Laboratory Mixture Containing Silica Fume (CPR7).

5.2 LONG-TERM CHLORIDE PENETRATION PROCEDURES

The Nordtest Bulk Diffusion (NTBuild 443) test and AASHTO T259 ponding test results after a 364-day exposure period were used as a benchmark to evaluate the conductivity tests. After their exposure period, each of the samples were profiled and tested using the FDOT standard test method FM5-516 to obtain their acid-soluble chloride ion content at varying depths.

The Bulk Diffusion procedure represents the most common test method of determining chloride diffusion coefficients for concrete specimens. This procedure is believed to simulate a "diffusion only" mechanism (Hooton, Thomas and Stanish 2001). The saturation of the samples, previous exposure to the chloride solution, eliminates the contribution by the absorption mechanism. Furthermore, the wicking effect is also eliminated with the sealing of all specimen faces except the one exposed to the NaCl solution. The diffusion coefficients are determined by fitting the data obtained in the chloride profiles analysis to Fick's Diffusion Second Law equation (see APPENDIX B). The measured chloride contents at varying depths are fitted to Fick's diffusion equation by means of a non-linear regression analysis in accordance with the method of least square fit. The Fick's Diffusion Second Law equation is presented as followed:

$$\mathrm{C}(x,t) = C_s - (C_s - C_i)\,erf\left(\frac{x}{\sqrt{4Dt}}\right)$$

where

$C(x,t)$ - chloride concentration, measured at depth x and exposure time t (% mass)
C_s - projected chloride concentration at the interface between the exposure liquid and test specimen that is determined by the regression analysis (% mass)
C_i - initial chloride-ion concentration of the cementitious mixture prior to the submersion in the exposure solution (% mass)
x - depth below the exposed surface (to the middle of a layer) (m)
D - chloride diffusion coefficient (m^2/s)
t - the exposure time (sec)
erf - error function (tables with values of the error function are given in standard mathematical reference books).

Figure 35 shows an example of the regression analysis for the determination of the diffusion coefficient. Profiles and curve fitting results for each concrete mixture are summarized in APPENDIX B.

The AASHTO T259 test has been traditionally the most widely used test method to evaluate the resistance of concrete to chloride ion penetration. This standardized test procedure, however, does not contain a recommended method to analyze the obtained profile information. Two of the more common methods noted in the literature, total integral chloride content and chloride diffusion coefficient, were chosen to analyze the data gathered in the present research.

The total integral chloride content represents the total quantity of chlorides that has penetrated the samples during the exposure period of exposure. It is calculated by integrating the area under the chloride profile curve from the surface of exposure to the point where the chloride background is reached (see Figure 36).

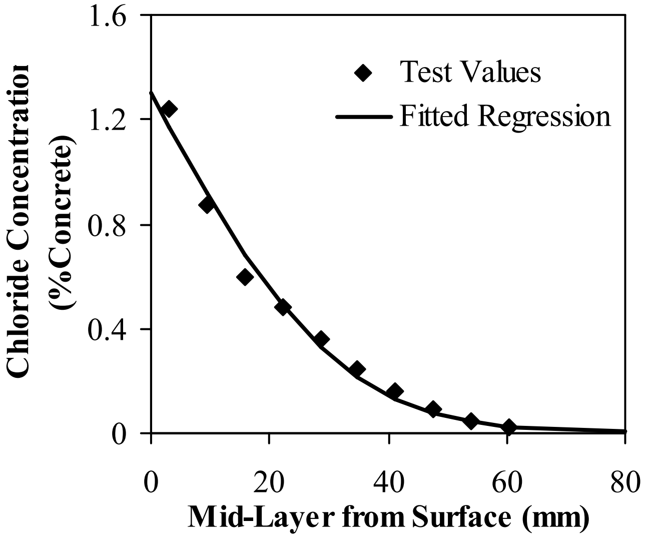


Figure 35. Bulk Diffusion Regression Analysis for CPR3 Mixture at 364-Days.

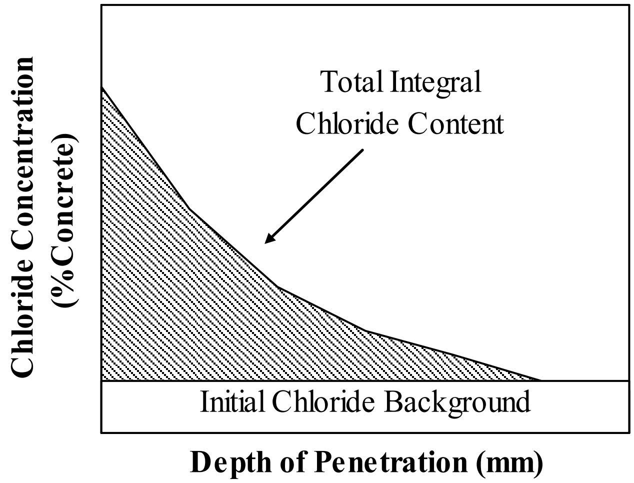


Figure 36. AASHTO T259 Total Integral Chloride Content Analysis.

The chloride diffusion coefficients were calculated for the AASHTO T259 results using the Bulk Diffusion data analysis procedures. The pure diffusion fitting approximation is not completely valid for the AASHTO T259 test. The testing set up induces other mechanisms of chloride intrusion other than pure diffusion. Absorption due to capillary suction of the unsaturated sample when it is exposed to the NaCl and vapor conduction (wicking) from the wet side face of the sample to the drier face are also present. The continuous exposure to the NaCl solution, however, causes the diffusion of chloride into the concrete under a static concentration gradient to dominate the chloride ingress, rather than a combination of diffusion and absorption (Scanlon and Sherman 1996). This approximation has been used in previous studies (McGrath and Hooton 1999; Hooton, Thomas and Stanish 2001) proving that it is a helpful technique of evaluation. This apparent diffusion coefficient will be denoted as in a previous research by

Hooton, Thomas and Stanish (2001) as “Pseudo-Diffusion Coefficient.” Profiles and curve fitting results for each concrete mixture are summarized in APPENDIX B.

The results from Bulk Diffusion and AASHTO T259 tests are compared in Figure 37 and Figure 38. The AASHTO T259 total integral chloride contents do not correlate well with that of the Bulk Diffusion coefficients (R^2 of 0.339). This corroborates previous finding by Hooton, Thomas and Stanish (2001) indicating that the total integral content measurement is not a good indicator of diffusion of chlorides in concrete. The method only takes into consideration the total amount of soluble chlorides for a particular depth. Significant information such as the shape of the chloride penetration curve is not reflected in this result. Comparison of the long-term diffusion coefficients gives a much better R^2 value of 0.829. Therefore, Pseudo-Diffusion result is selected as more appropriate method of analysis for AASHTO T259 method.

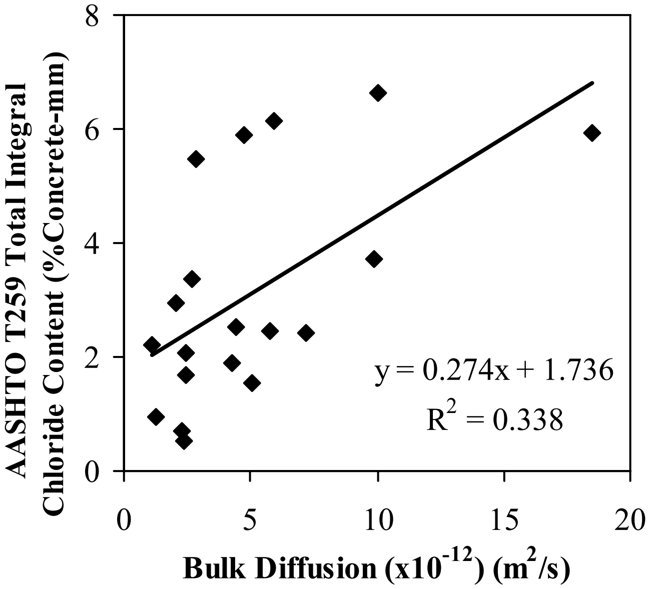


Figure 37. 364-Day AASHTO T259 Total Integral Chloride Content vs. 364-Day Bulk Diffusion.

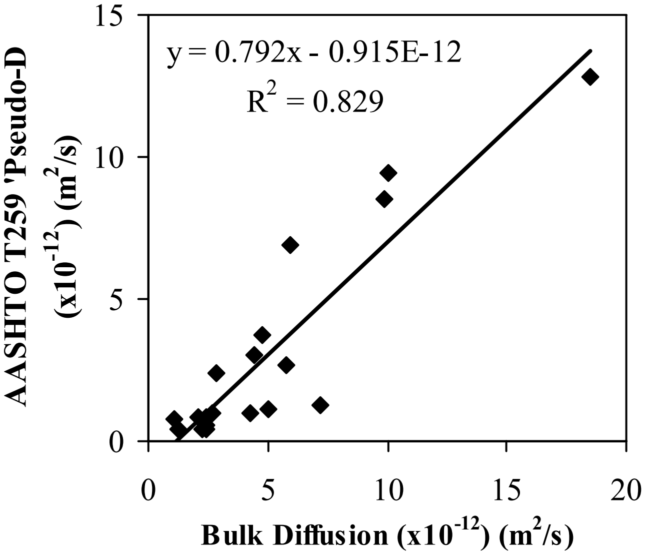
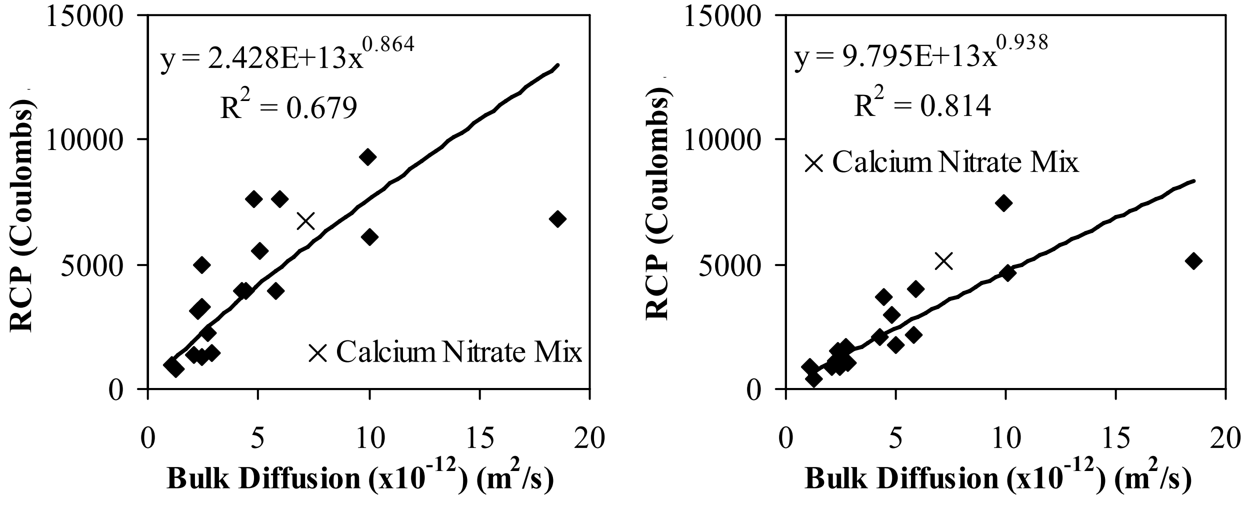


Figure 38. 364-Day AASHTO T259 Pseudo-Diffusion vs. 364-Day Bulk Diffusion.

5.3 SHORT-TERM CONDUCTIVITY TEST VALIDATIONS

5.3.1 RAPID CHLORIDE PERMEABILITY TEST (RCP)

The results of the Rapid Chloride Permeability tests (RCP) (AASHTO T277) at ages 14, 28, 56, 91, 182 and 364 days are compared to their respective 364-Day Bulk Diffusion and 364-Day AASHTO T259 Pseudo-Diffusion results in Figure 40. A number of curve forms were fit to the data and it was found that a power regression provided the best representation of the trends. Figure 39 and Figure 40 presents some detailed graphs of the test correlations with their respective derived least-square line-of-best fit.



(a) *(b)*

Figure 39. 364-Day Bulk Diffusion vs. RCP (AASHTO T277) at a) 28 Days and b) 91 Days.

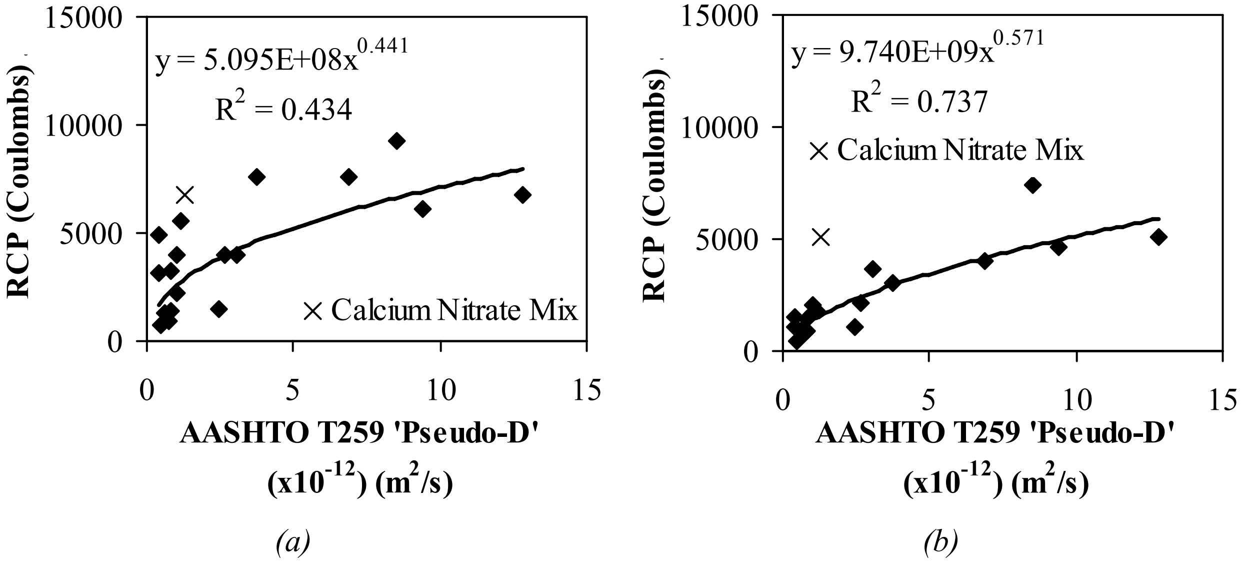


Figure 40. 364-Day AASHTO T259 Pseudo-Diffusion vs. RCP at a) 28 Days and b) 91 Days.

Previous research has shown that the RCP test method presents some limitations when applied to concrete modified with chemical admixtures as corrosion inhibitors (Shi, Stegemenn and Caldwell 1998). Concrete modified with a corrosion inhibitor such as calcium nitrite exhibits a higher coulomb value than the same concrete without the corrosion inhibitor when tested with the RCP test. Yet long-term chloride ponding tests have indicated that concrete with calcium nitrite is at least as resistant to chloride ion penetration as the control mixture. Results from the present project confirm the previous statement. Misleading results can be seen clearly from RCP test correlation with 364-Day AASHTO T259 Pseudo-Diffusion graphs (see Figure 40). The calcium nitrate mixture results did not follow the expected trend compared with the long-term reference. Higher values of coulombs were obtained from this mixture at both 28 and 91 days. Conversely, RCP results compared with the 364-Day Bulk Diffusion results do tend to follow the same trend as the other concrete mixtures (see Figure 39). The calcium nitrate effect, however, is represented by only one mixture on the entire specimen population. Consequently, there is not enough information to draw a solid final conclusion from the available data results. Therefore, the concrete mixture containing calcium nitrate (CPR12) was not included on the general correlations with long-term tests in order to establish a uniform level of comparison between all the electrical tests. General levels of agreement (R^2) to references are presented in Table 18. Moreover, detailed graphs with their least-squares line-of-best fit for the complete set of data are presented in APPENDIX C.

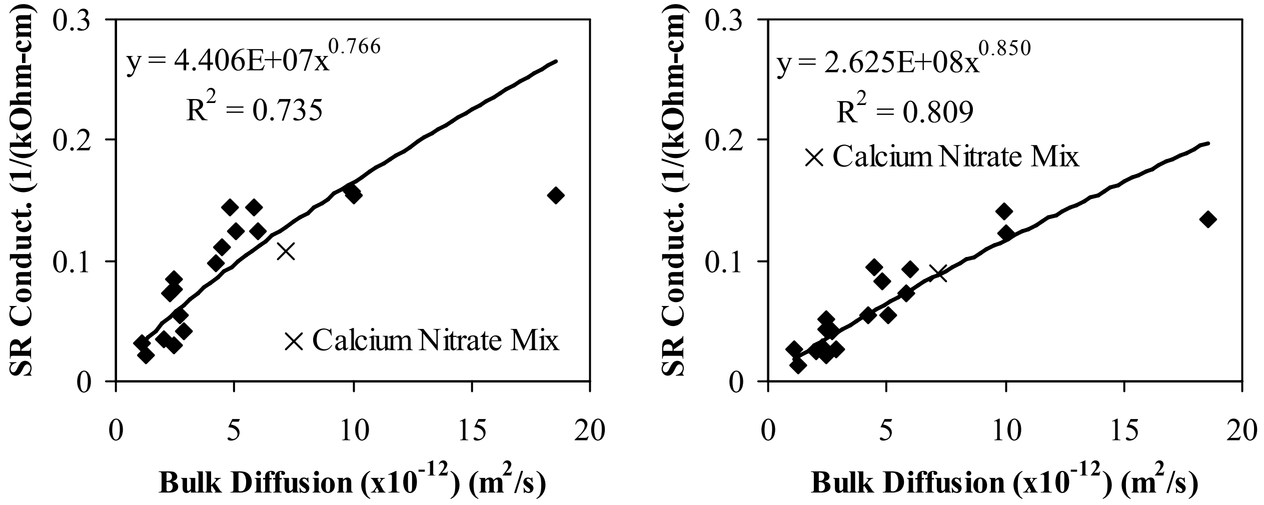
Table 18. Correlation Coefficients (R^2) of RCP to Reference Tests.

Test Procedure	Test Conducted Age (Days)	364-Day Bulk Diffusion (*)	364-Day AASHTO T259 Pseudo-Diffusion (*)	Number of Sample Sets
RCP (AASHTO T277)	14	0.60	0.32	18
	28	0.68	0.43	18
	56	0.82	0.65	18
	91	0.81	0.74	18
	182	0.79	0.84	18
	364	0.77	0.85	18

(*) Concrete Mixture Containing Calcium Nitrate (CPR12) was not included in the correlation.

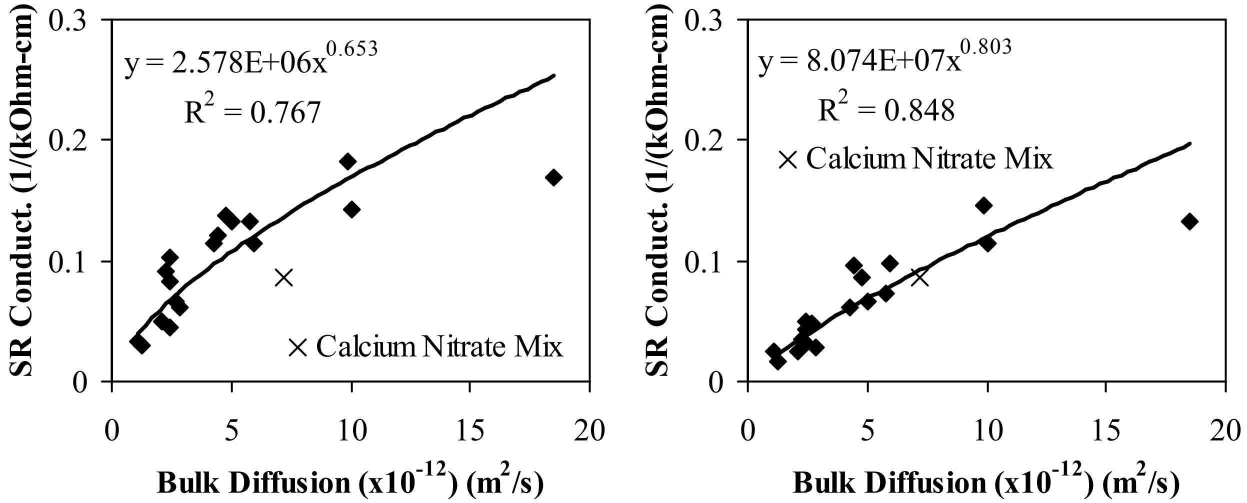
5.3.2 SURFACE RESISTIVITY

The electrical conductivity derived from the surface resistivity test was also compared with the two long-term diffusion reference tests. The surface resistivity test was conducted using two methods of curing, one at 100% humidity (moist cured) and the other in a saturated $Ca(OH)_2$ solution (lime cured). Surface resistivity results from the two curing regimens at 14, 28, 56, 91, 182, 364, 454 and 544 days of age are compared to their respective 364-Day Bulk Diffusion and 364-Day AASHTO T259 Pseudo-Diffusion results in linear plots. A mathematical curve-fitting was then derived for each of the test correlations. The power regression was selected as the most adequate trend relationship between the two set of test results. It was previously concluded on a previous section that the concrete mixture containing calcium nitrate (CPR12) was not to be included on the general correlations with long-term tests in order to establish a uniform level of comparison between the electrical tests. Concrete modified with a corrosion inhibitor as calcium nitrite exhibits misleading results on electrical resistivity tests (Shi, Stegemenn and Caldwell 1998). Figure 41 to Figure 44 show detailed graphs of the test correlations with their respective derived least-square line-of-best fit.



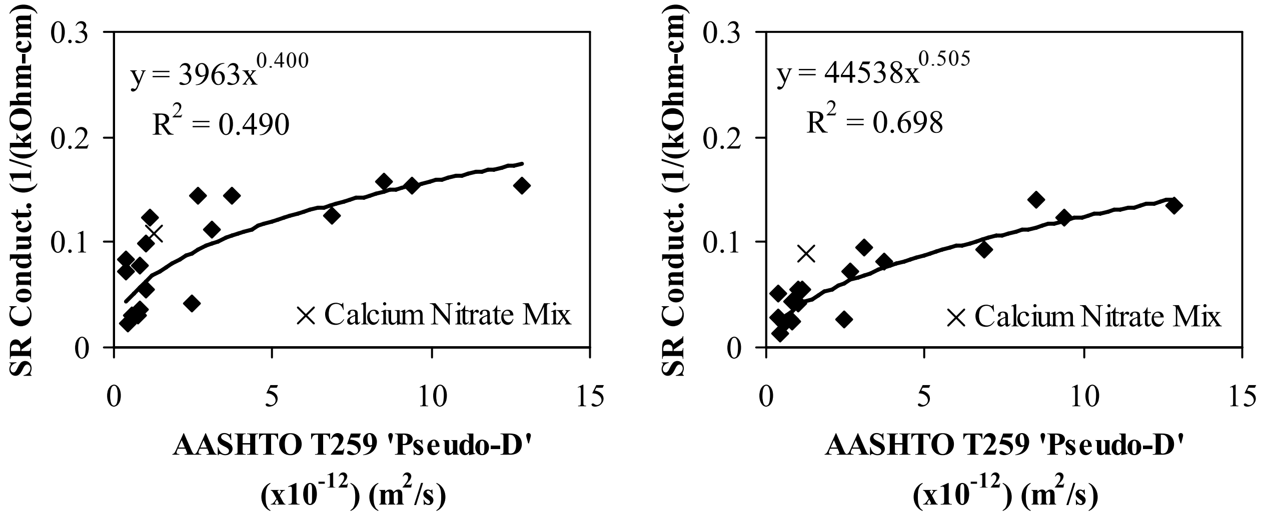
(a) *(b)*

Figure 41. 364-Day Bulk Diffusion vs. SR (Moist Cured) Conductivity at: a) 28 Days and b) 91 Days.



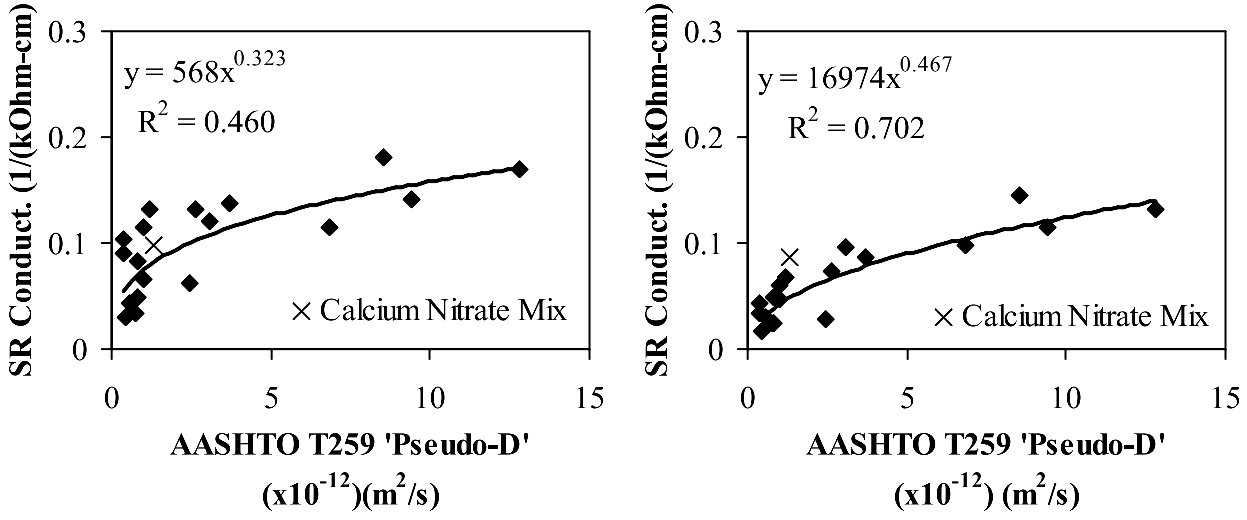
(a) *(b)*

Figure 42. 364-Day Bulk Diffusion vs. SR (Lime Cured) Conductivity at: a) 28 Days and b) 91 Days.



(a) *(b)*

Figure 43. 364-Day AASHTO T259 Pseudo-Diffusion vs. SR (Moist Cured) Conductivity at: a) 28 Days and b) 91 Days



(a) *(b)*

Figure 44. 364-Day AASHTO T259 Pseudo-Diffusion vs. SR (Lime Cured) Conductivity at: a) 28 Days and b) 91 Days.

The surface resistivity results for the two curing regimens are compared in Figure 45 and Figure 46. The figures show the R^2 results for the Bulk Diffusion and AASHTO T259 Pseudo-Diffusion correlation, respectively. The comparison between the two curing procedures shows little difference. A relative gain in correlation, however, was observed for the moist cured regimen at 14 days of age. The difference in the number of samples tested at that age (see Table 19) might explains the relative increase on the correlation. Fewer samples were correlated for the moist cured than the lime cured specimens. Consequently, the probability of fitting a set of data increases for fewer number of records. Therefore, it is concluded that either of the methods will derive on equal surface resistivity behavior. General levels of agreement (R^2) to references for both curing methods are presented in Table 19. Moreover, detailed graphs with their least-squares line-of-best fit for the complete set of data are presented in APPENDIX C.

Table 19. Correlation Coefficients (R^2) of SR to Reference Tests.

Test Procedure	Test Conducted Age (Days)	364-Day Bulk Diffusion (*)	364-Day AASHTO T259 Pseudo-Diffusion (*)	Number of Sample Sets
Surface Resistivity (Lime Cured)	14	0.48	0.27	18
	28	0.77	0.46	18
	56	0.81	0.58	18
	91	0.85	0.70	18
	182	0.81	0.78	18
	364	0.70	0.82	18
	454	0.70	0.81	18
	544	0.68	0.78	18
Surface Resistivity (Moist Cured)	14	0.76	0.67	13 (**)
	28	0.74	0.49	18
	56	0.75	0.53	18
	91	0.81	0.70	18
	182	0.79	0.81	18
	364	0.76	0.80	18
	454	0.71	0.78	18
	544	0.68	0.77	18

(*) Concrete Mixture Containing Calcium Nitrate (CPR12) was not included in the correlation.
(**) Fewer set of samples were available for this correlation.

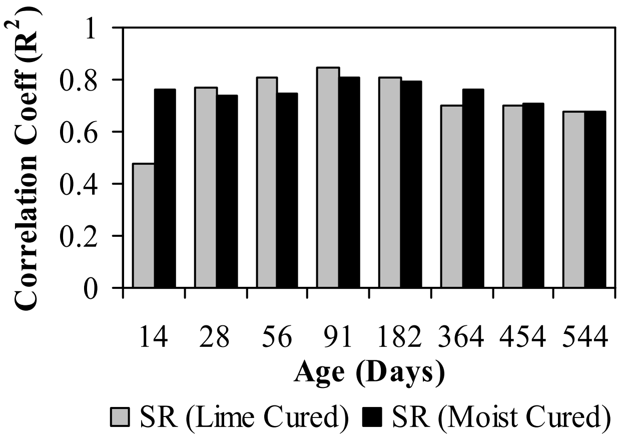


Figure 45. SR Curing Method Comparison of Correlation Coefficients with 364-Day Bulk Diffusion Test.

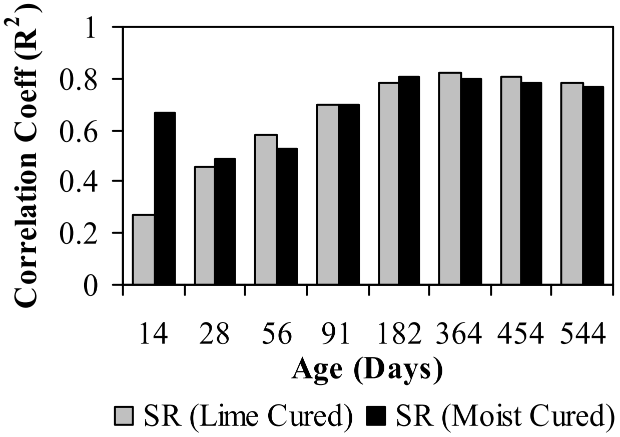


Figure 46. SR Curing Method Comparison of Correlation Coefficients with 364-Day AASHTO T259 Pseudo-Diffusion Test.

5.3.3 Rapid Migration Test (RMT)

Data collected from the rapid migration test (RMT) procedure is used to calculate a diffusion coefficient. This diffusion coefficient (D_{RMT}) is calculated according to the analytical derivation presented as followed:

$$D_{RMT} = \frac{R.T.L}{z.F.(U-2)} \cdot \frac{x_d - \alpha.\sqrt{x_d}}{t}$$

$$\alpha = 2\sqrt{\frac{R.T.L}{z.F.(U-2)}} \cdot \mathrm{erf}^{-1}\left(1 - \frac{2.C_d}{C_o}\right)$$

where D_{RMT}: non-steady-state chloride migration coefficient, m^2/s; z: absolute value of ion valence, for chloride z = 1; F: Faraday constant, $F = 9.648 \times 10^4$ J/(V.mol); U: Absolute value of the applied voltage, V; R: universal gas constant, R = 8.314 J/(K.mol); T: average value of the initial and final temperature in the anolyte solution, K; L: thickness of the specimen, m; x_d: average value of the penetration depths, m; t: test duration, s; erf^{-1}: inverse of error function; C_d: chloride concentration at which the color changes, $C_d = 0.07$ N for OPC concrete; C_o: chloride concentration in the catholyte solution, $C_o = 2$ N.

One of the parameters used in this equation is the average depth of chloride penetration as determined by the color change boundary caused by the silver nitrate solution. At the beginning of the project, a different analysis approach was chosen. RMT specimens were profiled at varying depths to obtain their respective chloride content in accordance with the standard test method FM 5-516. Therefore, a method of converting these chloride profile results to a boundary depth of penetration was needed.

Otsuki et al. (1992) reported a relatively constant value of 0.15% of water-soluble chloride concentration by weight of cement for the investigated pastes, mortar and concrete with different water/cement ratios. The coefficient of variation of the studied values was not reported. On the other hand, subsequent researches have found high variability in the chloride concentrations correlations with the color-change boundary (Sirivivatnanon and Khatri 1998;

Andrade et al. 1999; Meck and Sirivivatnanon 2003). Average results ranging between 0.12% to 0.18% by weight of concrete and 0.9% to 1.2% by weight of the binder at the color-change boundary have been found (see Table 4). These results also reported coefficients of variation as high as 49%.

A validation process was executed for the current research due to the lack of agreement concerning the corresponding chloride concentration to the color-change boundary. A set of 63 samples were evaluated by applying the two methods to the same sample. The samples were axially split; chloride content was measured on one half with FM 5-516 and colorimetric penetration was calculated on the other half by spraying silver nitrate solution. Three ¼-inch (6.4-mm) slices were analyzed by the FM 5-516 method to determine the chloride content. In most of the cases, the color-change boundary measured by the colorimetric technique coincided within the range of the three point chloride profile. However, profile extrapolation was needed in some cases in order to reach the measured penetration. As a result, a curve fitting approximation was used to predict the results. Fick's Diffusion Second Law was then used to generate the chloride content profile. These profiles were then used to determine the chloride percentage associated with the actual measured depth obtained by the colorimetric procedure. Figure 47 and Figure 48 show examples of how the chloride concentration by weight of the concrete can be derived from the measured color-change boundary penetration. Detailed illustration for each sample can be found in APPENDIX C. Additionally, summary of average chloride concentration found at the color-change boundary and their statistical parameters are presented in Table 20.

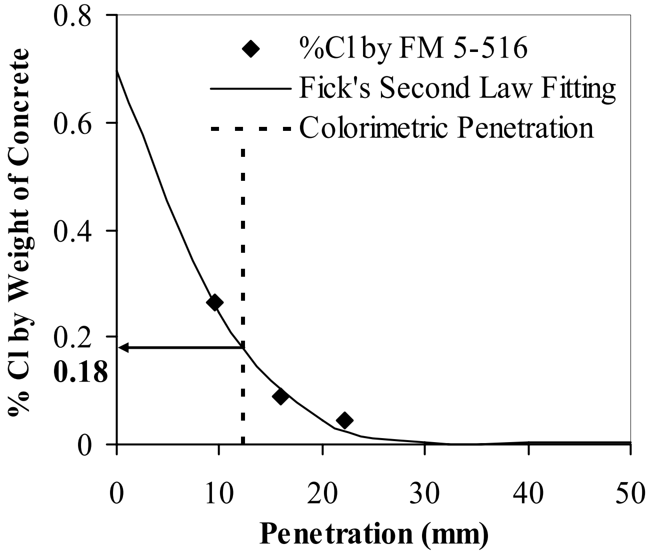


Figure 47. Chloride Concentration by Weight of Concrete Derived from Measured Color-Change Boundary Penetration (CPR2 RMT at 182-Days).

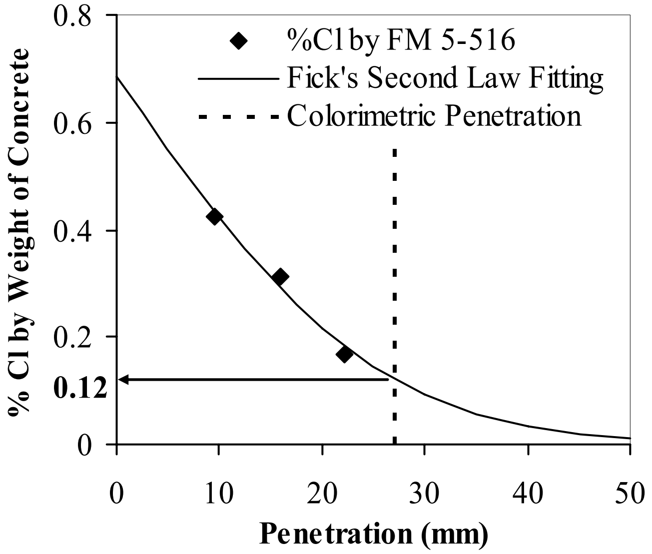
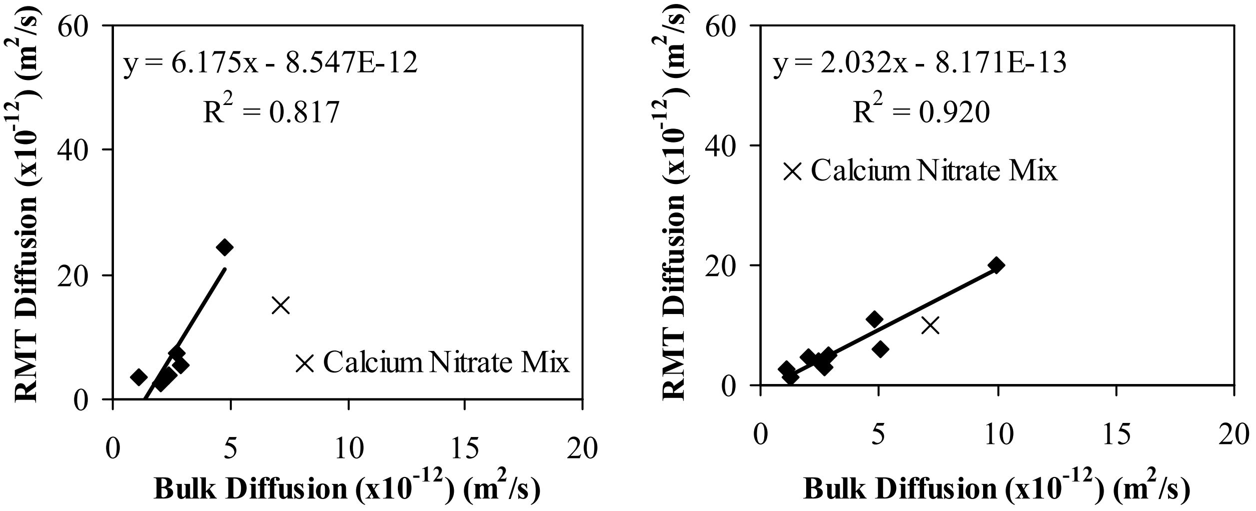


Figure 48. Chloride Concentration by Weight of Concrete Derived from Measured Color-Change Boundary Penetration (CPR3 RMT at 364-Days).

Table 20. Average Chloride Concentrations Found at the Color-Change Boundary and Statistical Parameters.

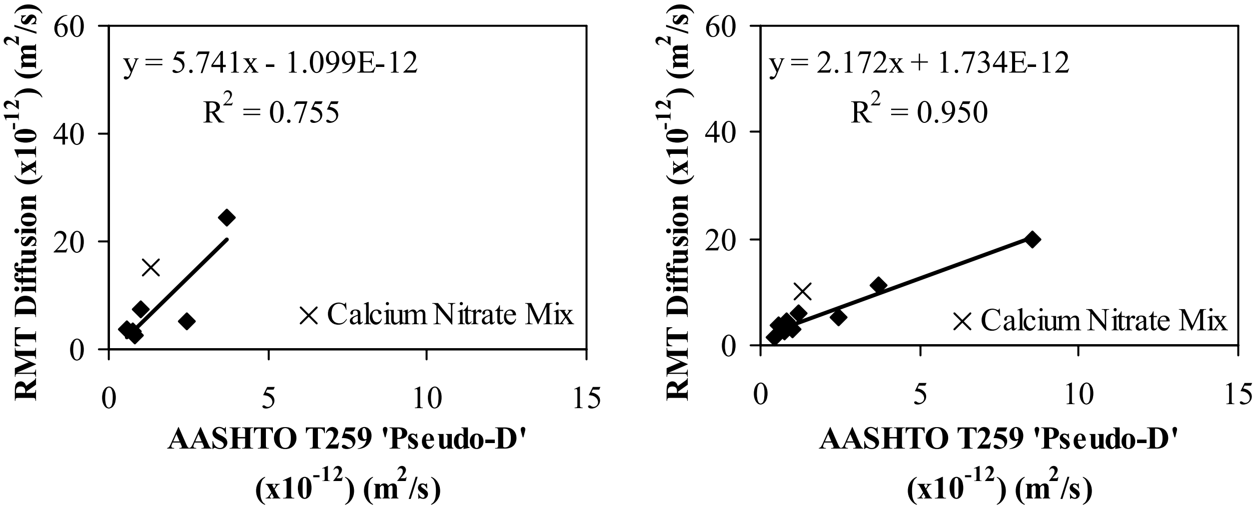
Chloride Concentration	Min.	Max.	Average	Standard deviation	Coefficient of variation (%)	Number of observations
% by weight of concrete	0.02	0.30	0.14	0.06	40.28	63
% by weight of binder	0.11	1.57	0.74	0.30	41.13	63

An average of chloride concentration by weight of concrete at the measured penetration of 0.14% was found by this evaluation. The obtained result reasonably agrees with previous research findings (Sirivivatnanon and Khatri 1998; Andrade et al. 1999; Meck and Sirivivatnanon 2003). On the other hand, it presents quite a high coefficient of variation of 40.28%. Therefore, inaccurate RMT diffusion coefficient results will be a consequence of erroneously derived depth of penetration. This affects the first set of samples tested where only chloride profiles information were measured (see Table 16). Therefore, RMT diffusion coefficients were calculated only on samples where the colorimetric information was available. A better understanding concerning the limit which the color-change boundary takes place is required. The reported RMT diffusion results were correlated with the two long-term diffusion reference values 364-Day Bulk Diffusion and 364-Day AASHTO T259 Pseudo-Diffusion. Figure 49 and Figure 50 show some graphs of the test correlations with their respective derived least-square line-of-best fit. Detailed illustration for each sample can be found in APPENDIX C. Additionally, a summary of the general levels of agreement (R^2) of the different correlations are presented in Table 21.



(a) *(b)*

Figure 49. 364-Day Bulk Diffusion vs. RMT Diffusion at a) 28 Days and b) 91 Days.



(a) *(b)*

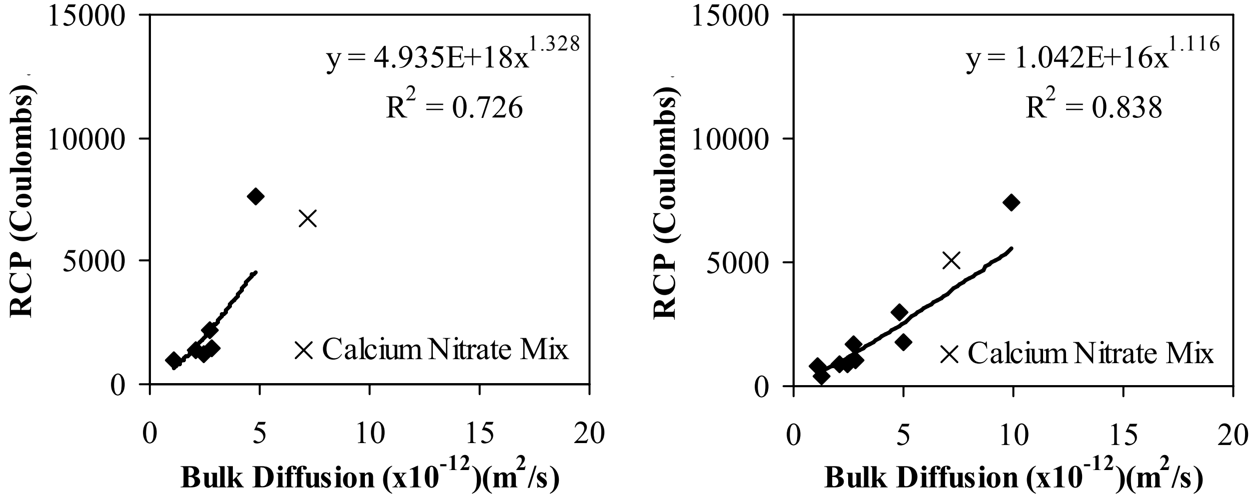
Figure 50. 364-Day AASHTO T259 Pseudo-Diffusion vs. RMT Diffusion at a) 28 Days and b) 91 Days.

Table 21. Correlation Coefficients (R^2) of RMT Diffusion Results to Reference Tests.

Test Procedure	Test Conducted Age (Days)	364-Day Bulk Diffusion (*)	364-Day AASHTO T259 Pseudo-Diffusion (*)	Number of Sample Sets
RMT (NTBuild 492)	14	0.90	0.87	6
	28	0.82	0.76	6
	56	0.84	0.77	6
	91	0.92	0.95	9
	182	0.86	0.92	16
	364	0.77	0.95	18

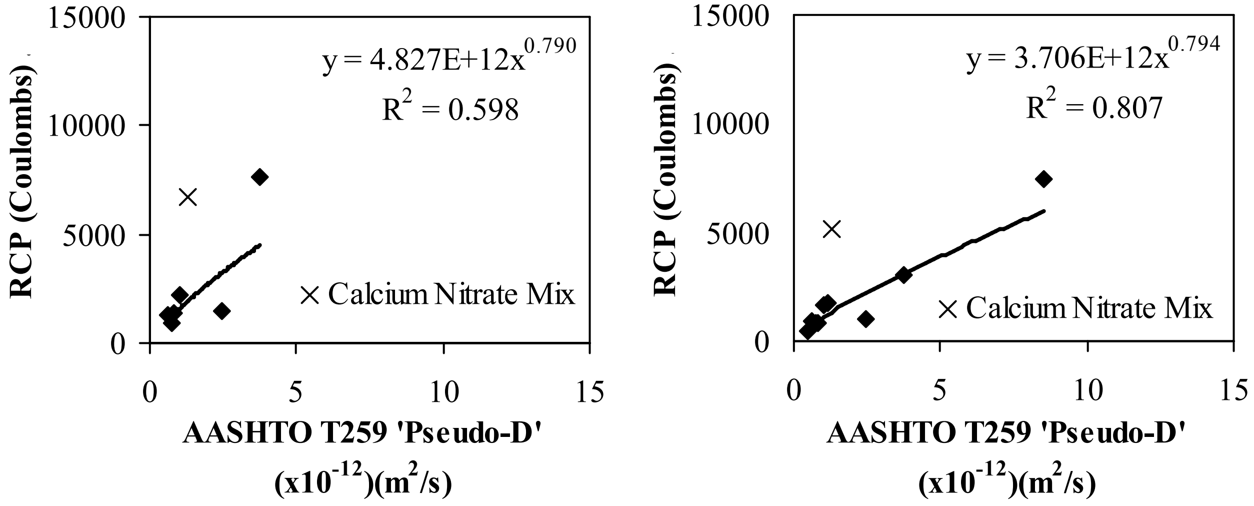
(*) Concrete Mixture Containing Calcium Nitrate (CPR12) was not included in the correlation.

The RMT procedure has high level of agreement with both reference test results. Moreover, the RMT diffusion coefficient results followed an expected logical trend compared with the long-term diffusion references. However, the RMT correlated samples population is considerably lower compared with other evaluated conductivity tests in this research. Therefore, an additional approach to compare the RMT test with the other conductivity tests was made. RCP and SR test correlations to the reference tests were recalculated for the same mixtures that RMT results were available to ensure that each method had the same number of samples for the statistical calculations. Figure 51 to Figure 56 show some graphs of the test correlations with their respective derived least-square line-of-best fit. Detailed illustration for each sample can be found in APPENDIX C. Additionally, a summary of the general levels of agreement (R^2) of the different correlations are presented in Table 22 and Table 23.



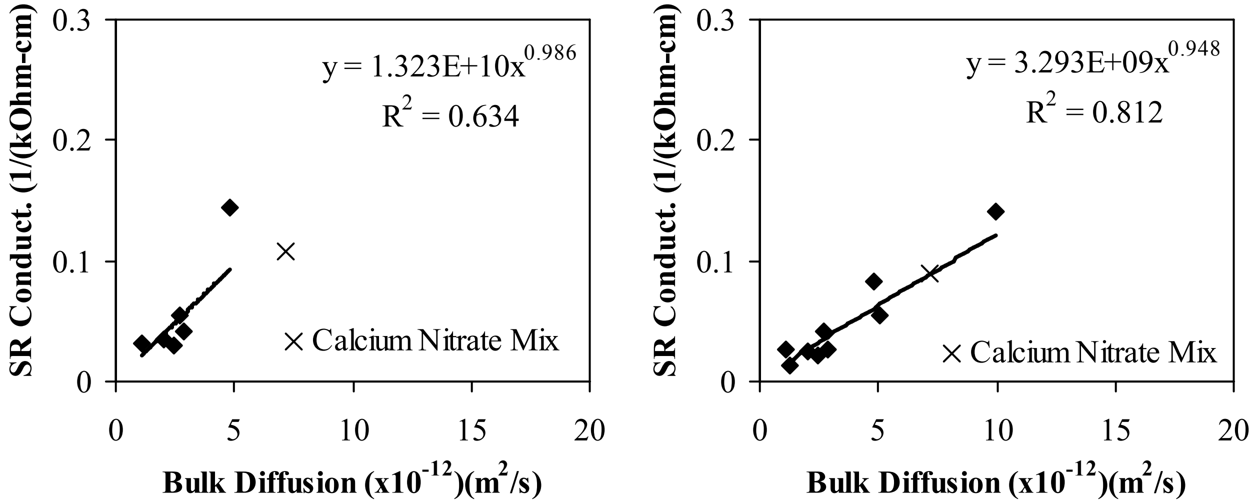
(a) *(b)*

Figure 51. 364-Day Bulk Diffusion vs. RCP (Only Mixtures for which RMT Results were Available) at a) 28 Days and b) 91 Days.



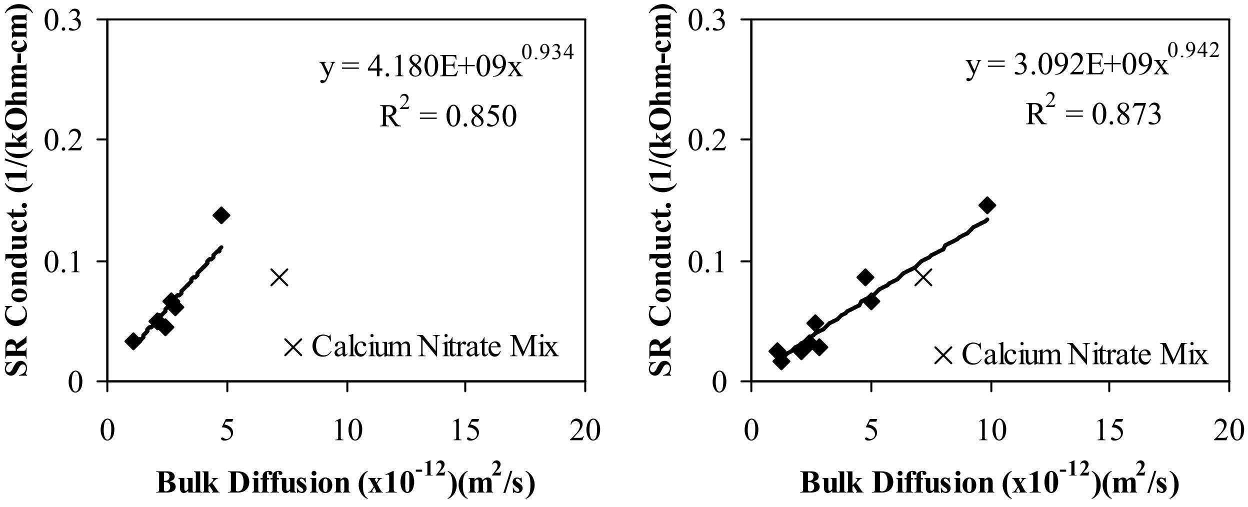
(a) *(b)*

Figure 52. 364-Day AASHTO T259 Pseudo-Diffusion vs. RCP (Only Mixtures for which RMT Results were Available) at a) 28 Days and b) 91 Days.



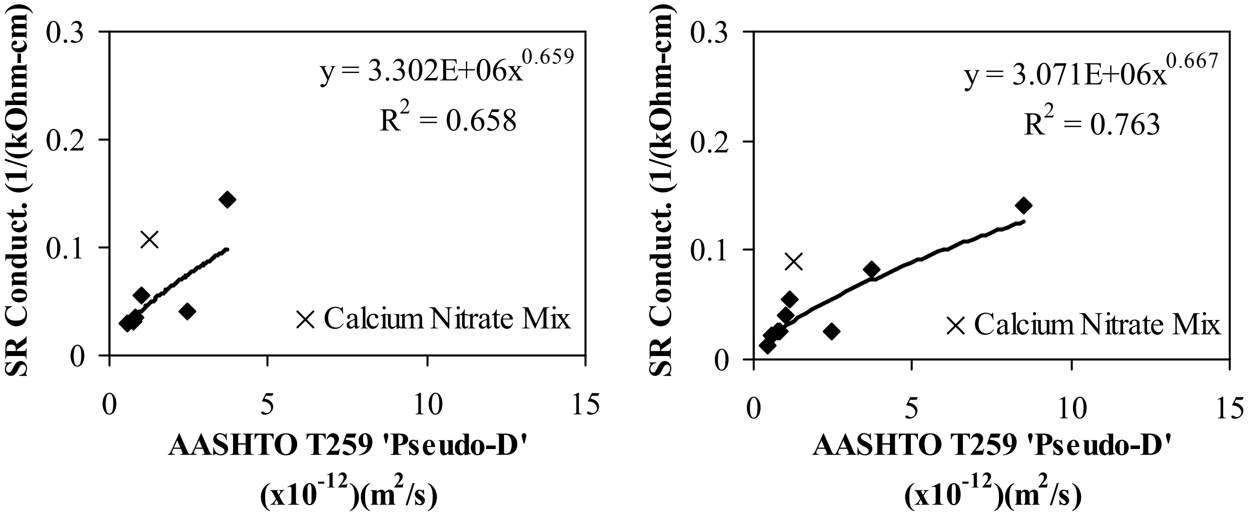
(a) *(b)*

Figure 53. 364-Day Bulk Diffusion vs. SR (Moist Cured) Conductivity (Only Mixtures for which RMT Results were Available) at a) 28 Days and b) 91 Days.



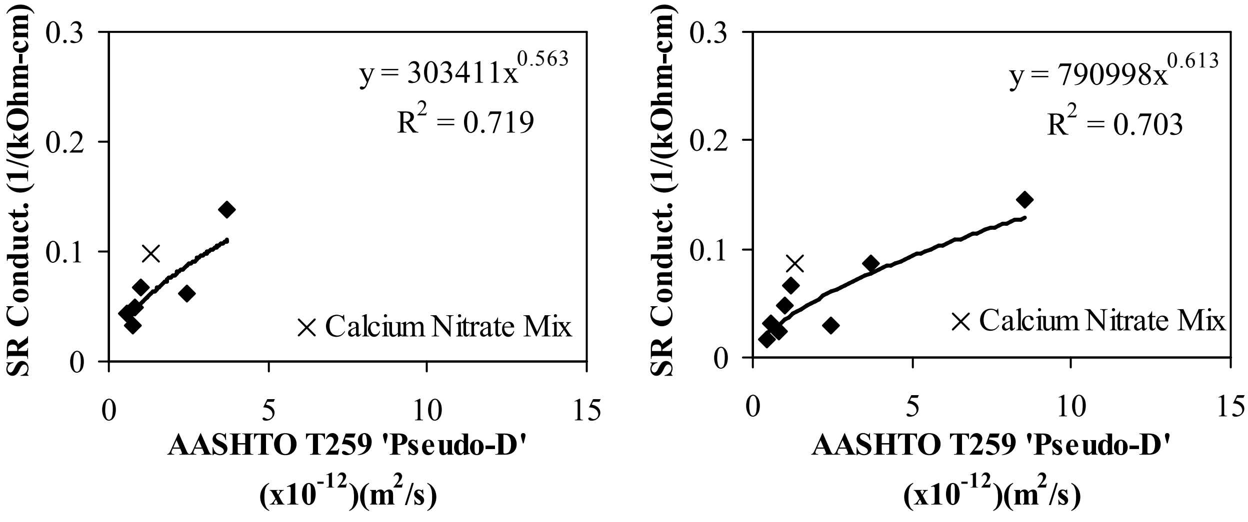
(a) *(b)*

Figure 54. 364-Day Bulk Diffusion vs. SR (Lime Cured) Conductivity (Only Mixtures for which RMT Results were Available) at a) 28 Days and b) 91 Days.



(a) *(b)*

Figure 55. 364-Day AASHTO T259 Pseudo-Diffusion vs. SR (Moist Cured) Conductivity (Only Mixtures for which RMT Results were Available) at a) 28 Days and b) 91 Days.



(a) *(b)*

Figure 56. 364-Day AASHTO T259 Pseudo-Diffusion vs. SR (Lime Cured) Conductivity (Only Mixtures for which RMT Results were Available) at a) 28 Days and b) 91 Days.

Table 22. Correlation Coefficients (R^2) of RCP to Reference Tests (only mixtures for which RMT results were available).

Test Procedure	Test Conducted Age (Days)	364-Day Bulk Diffusion (*)	364-Day AASHTO T259 Pseudo-Diffusion (*)	Number of Sample Sets
RCP (AASHTO T277)	14	0.79	0.70	6
	28	0.73	0.60	6
	56	0.62	0.55	6
	91	0.84	0.81	9
	182	0.78	0.86	16
	364	0.77	0.85	18

(*) Concrete Mixture Containing Calcium Nitrate (CPR12) was not included in the correlation.

Table 23. Correlation Coefficients (R^2) of SR to Reference Tests (Only Mixtures for which RMT Results were Available).

Test Procedure	**Test Conducted Age (Days)**	**364-Day Bulk Diffusion (*)**	**364-Day AASHTO T259 Pseudo-Diffusion (*)**	**Number of Sample Sets**
Surface Resistivity (Lime Cured)	14	0.70	0.69	6
	28	0.85	0.72	6
	56	0.70	0.57	6
	91	0.87	0.70	9
	182	0.81	0.82	16
	364	0.70	0.82	18
Surface Resistivity (Moist Cured)	14	0.71	0.75	6
	28	0.63	0.66	6
	56	0.59	0.61	6
	91	0.81	0.76	9
	182	0.78	0.84	16
	364	0.76	0.80	18

(*) Concrete Mixture Containing Calcium Nitrate (CPR12) was not included in the correlation.

The R^2 results of the conductivity test correlations to the reference tests are compared in Figure 57 and Figure 58. In all cases, the correlations between the RMT and the long-term tests were equal or slightly better than those obtained by the RCP and SR tests. Even though the number of mixtures in this analysis is reduced, all the samples contained pozzolans (such as fly ash, silica fume, ground granulated blast-furnace slag or Metakaolin). This corroborates previous findings by Hooton, Thomas and Stanish (2001) indicating that the RMT is less affected by the presence of supplementary cementitious materials. Therefore, RMT test was applicable to wider range mineral admixtures in concrete than the RCP and SR tests.

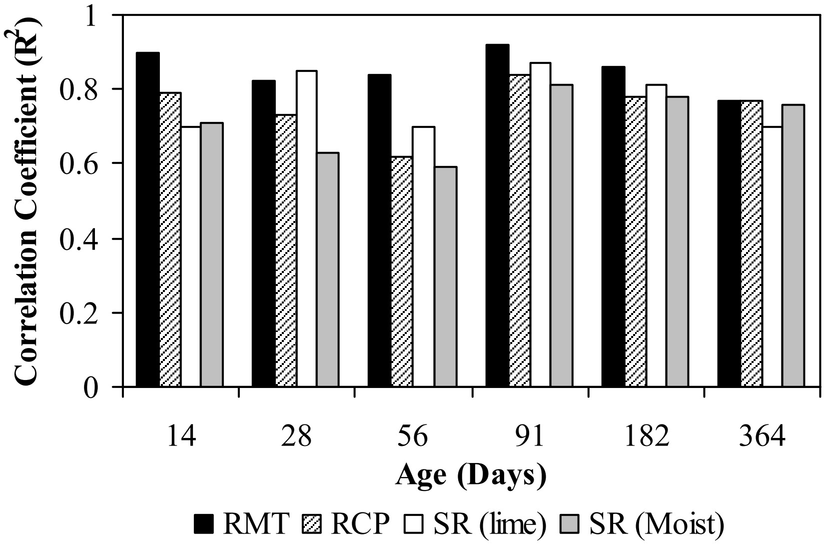


Figure 57. Short-Term Conductivity Test Comparison (Only Mixtures for which RMT Results were Available) of Correlation Coefficients with 364-Day Bulk Diffusion Test.

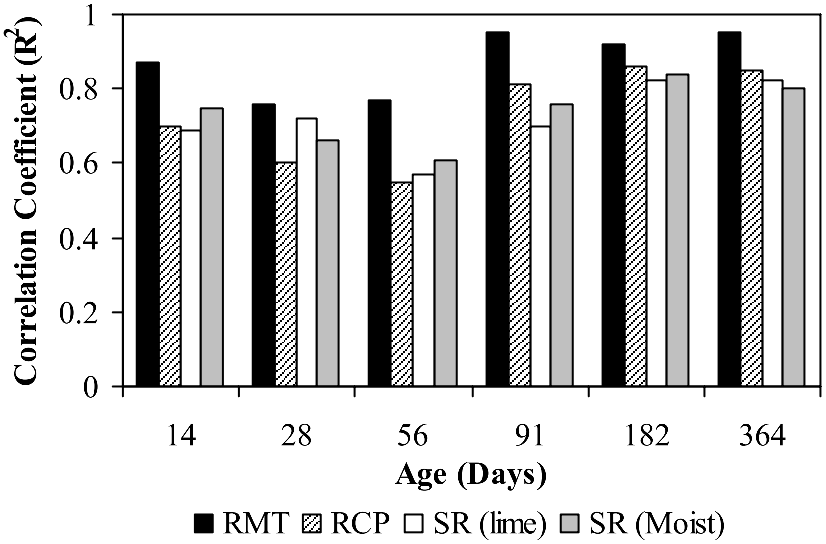


Figure 58. Short-Term Conductivity Test Comparison (Only Mixtures for which RMT Results were Available) of Correlation Coefficients with 364-Day AASHTO T259 Pseudo-Diffusion.

5.3.4 IMPRESSED CURRENT

Laboratory results from the electrochemical test impressed current (FM 5-522) are presented on APPENDIX C and summarize in Figure 59. The compiled result graph shows a logical trend of agreement where low electrical resistance samples tend to fail at early ages compared with specimens with high resistance readings that fail at more advance ages. The longer time-to-failure and higher resistance indicates an improvement over the different mixtures and also an improvement in the concrete protective properties against corrosion (Larsen et al. 1975). Impressed current results of conductivity (inverse of resistance) and the time-to-failure were correlated with the two long-term diffusion reference tests, 364-Day Bulk Diffusion and 364-Day AASHTO T259 Pseudo-Diffusion. General levels of agreement (R^2) are presented on Table 24 and detailed graphs with their least-squares line-of-best fit are shown in Figure 60 and Figure 61. Electrical conductivity results correlated better than time-to-failure results of the reference tests. However, the ranges of level of agreement obtained from this test are considerably lower than the other short-term methods presented previously when tested at their optimal age. This can be related to the fact that the scope of the impressed current test was not intended to be a predictor of long-term chloride permeability. The accelerated laboratory procedure was designed as a qualitative measurement for corrosion protective properties of concrete and rebar claddings and coatings. Nevertheless, it represents as a helpful tool for comparing various types of concrete mixtures.

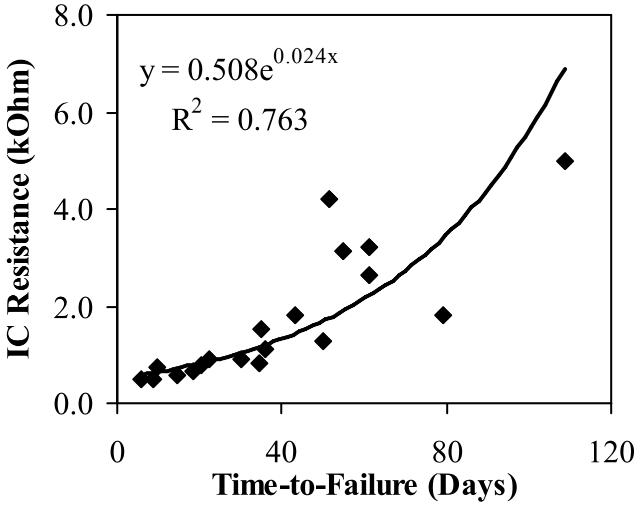
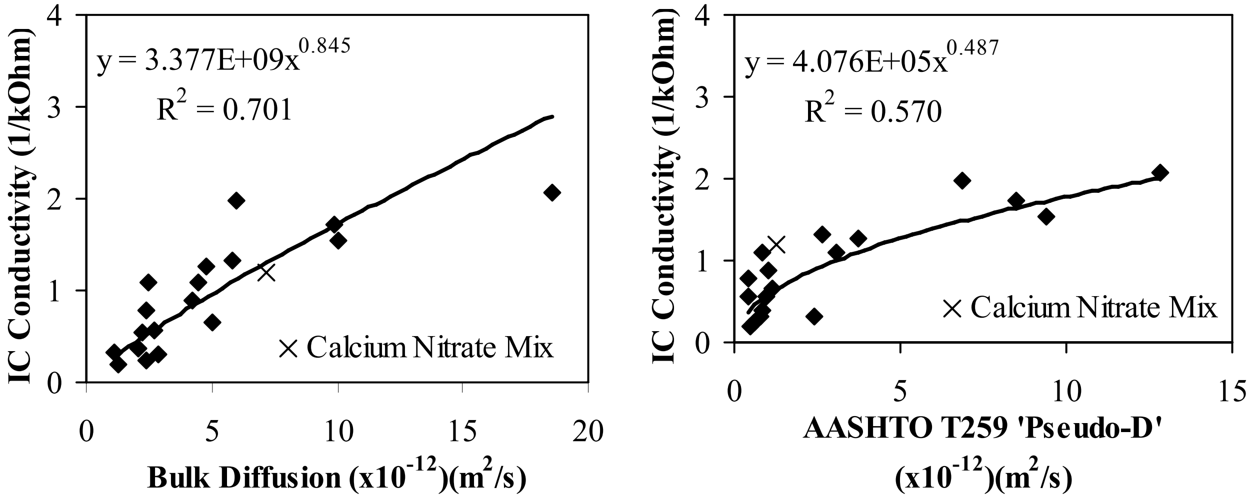
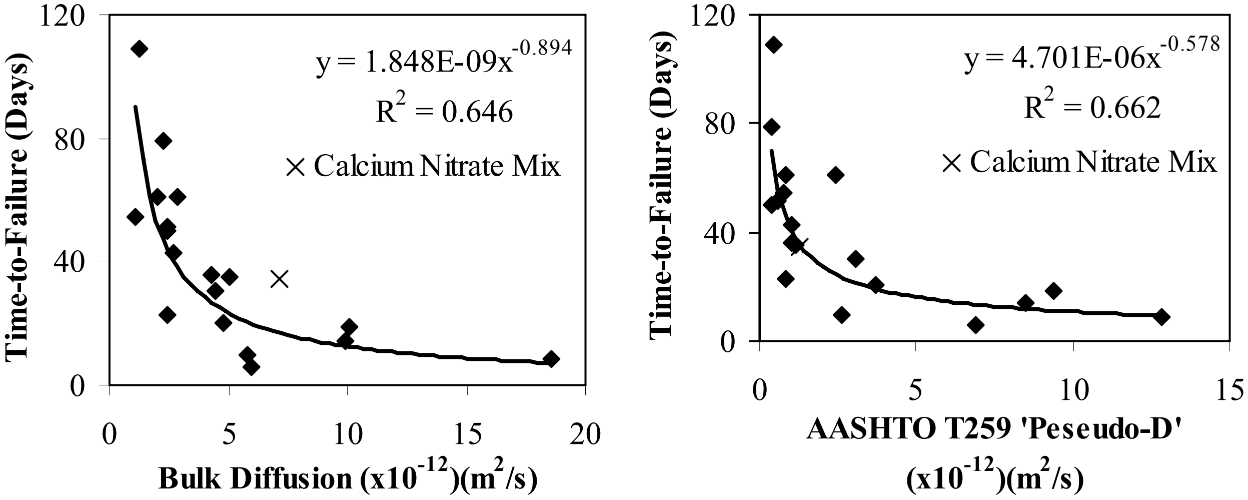


Figure 59. Impressed Current Time-to-Failure vs. Average Daily Resistance.



(a) *(b)*

Figure 60. Impressed Current Conductivity vs.: a) 364-Day Bulk Diffusion and b) 364-Day AASHTO T259 Pseudo-Diffusion.



(a) *(b)*

Figure 61. Impressed Current Time-to-Failure vs. a) 364-Day Bulk Diffusion and b) 364-Day AASHTO T259 Pseudo-Diffusion.

Table 24. Correlation Coefficients (R^2) of Impressed Current Results to Reference Tests.

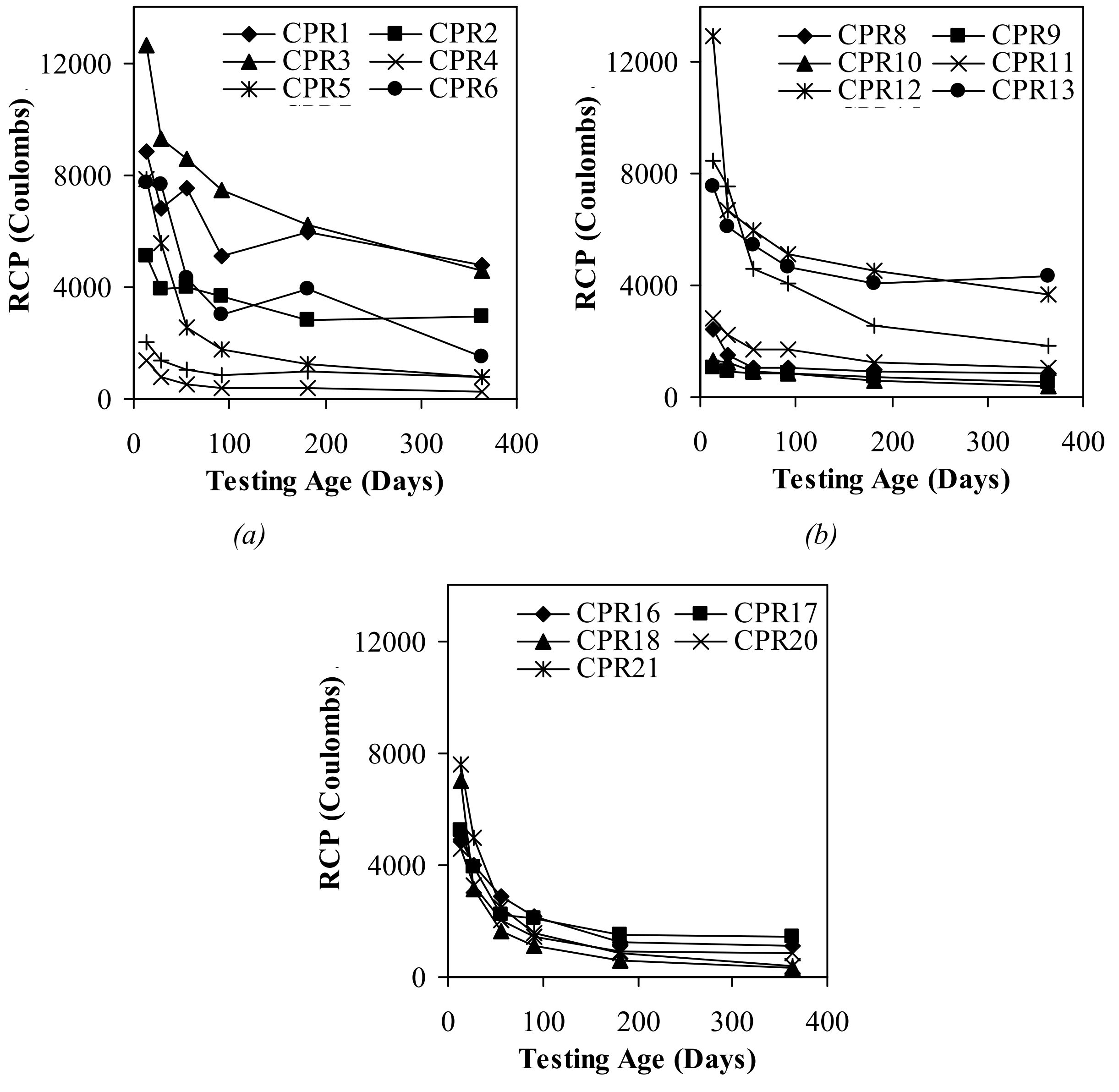
Test Procedure	364-Day Bulk Diffusion	364-Day AASHTO T259 Pseudo-Diffusion
Impressed Current Conductivity	0.70	0.57
Impressed Current Time-to-Failure	0.65	0.66

6 DATA ANALYSIS – Relating Electrical Tests and Bulk Diffusion

The commonly selected 1000 coulombs limit for RCP has been chosen based on a scale reported on the standardized test procedure (see Table 1). This scale presents a qualitative method that relates the equivalent measured charge in coulombs to the chloride ion permeability of the concrete. The original research program that derived the rating scale (Whiting 1981) was based upon a reduced amount of single core concrete samples that did not include pozzolans or corrosion inhibitors. The set of data results were linearly fitted (R^2 of 0.83) and five qualitative ranges of chloride permeability were defined based on the total integral chloride values.

The appropriateness of the test has been considered extensively in the literature (Whiting 1981; Whiting 1988; Whiting and Dziedzic 1989; Ozyildirim and Halstead 1988; Scanlon and Sherman 1996) with samples containing a wide variety of pozzolans and corrosion inhibitors. They have demonstrated no consistent correlation between the RCP results and the rates of chloride permeability measured with standard procedure. This indicates that the RCP test was never intended as a quantitative predictor of chloride permeability into any given concrete (Pfeifer, McDonald and Krauss 1994). The test was designed as a quality control procedure that should be calibrated with long-term tests. As stated in the scope of the RCP standard method, the rapid test procedure is applicable to types of concrete in which correlations have been established between this rapid test procedure and long-term chloride ponding tests. Incorrect interpretation of the rapid electrical values can be made relying entirely on RCP results. Consequently, in this section, the data from the RCP short-term electrical tests is correlated with the results of the bulk diffusion tests to obtain better information concerning the performance of Florida concrete.

The original RCP coulomb limits (see Table 1) were derived from correlations between 90-day RCP samples and 90-day AASHTO T259 total integral chloride. Therefore, the use of these restrictions on lower testing ages, as 28 days, represents a conservative approach of inspection. The electrical conductivity of concrete decreases with time as the process of hydration takes place. Figure 62 shows the reduction of the RCP coulomb values as the testing age increase. Results show a higher rate of RCP coulombs decrease for the first 91 days of curing, followed by a relative stable flat trend in most of the cases.

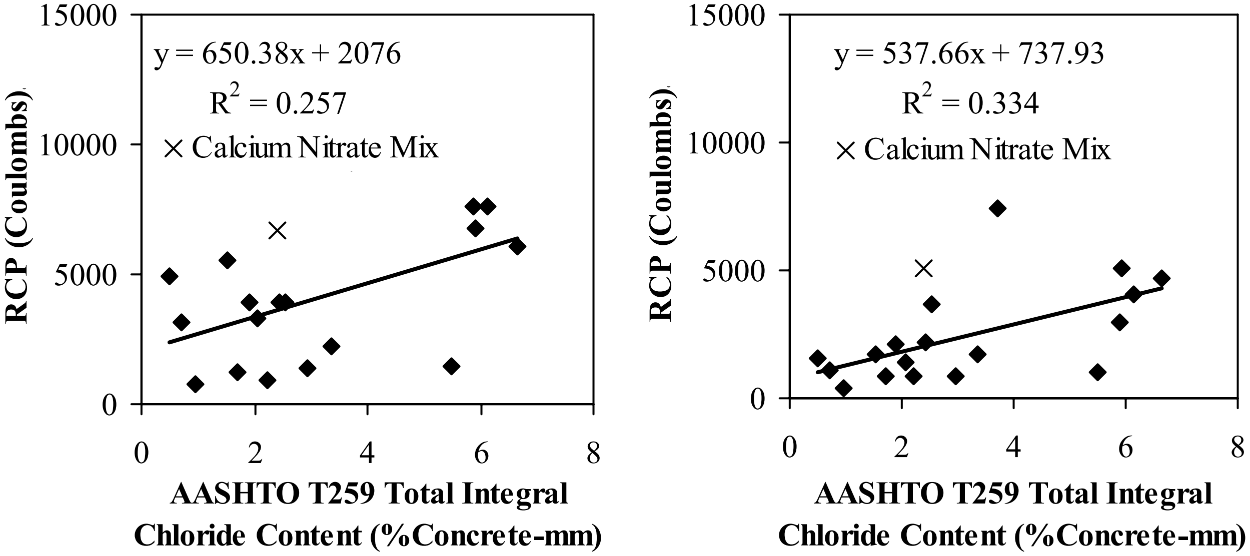


(a) *(b)*

(c)

Figure 62. RCP Test Coulomb Results Change With Age for: (a) CPR1 to CPR7 Mixtures, (b) CPR8 to CPR15 Mixtures and (c) CPR16 to CPR21 Mixtures.

Following the basis of Whiting's original research program (Whiting 1981), an initial attempt of correlating the collected data was made. AASHTO T259 total integral chloride at 364 days was linearly correlated to the RCP results at different testing ages. Figure 63 shows some detailed graphs of the test correlations with their respective derived line-of-best fit equations. The RCP results do not correlate well with those of the AASHTO T259 total integral chloride (R^2 values ranging between 0.11 to 0.43). This corroborates previous findings presented on the long-term chloride penetration procedures section indicating that total integral content is not a good indicator of diffusion of chlorides in concrete. Therefore, a different approach to analyze the RCP results is needed. Detailed graphs for the complete set of data are presented in APPENDIX C.



(a) *(b)*

Figure 63. 364-Day AASHTO T259 Total Integral Chloride Content vs. RCP at: (a) 28 Days and (b) 91 Days.

A second attempt to calibrate the RCP standard results was based on the correlation of the test results to the diffusion coefficients derived from the reference tests AASHTO T259 and Bulk Diffusion. The measured coulombs at different testing ages were correlated to the two reference test diffusion results (see Table 18). The level of agreements (R^2) obtained for each RCP testing age are compared in Figure 64 and Figure 65. The RCP trend of agreement reaches a maximum value on samples tested at 91 days when compared to those of 364-day Bulk Diffusion. On the other hand, RCP samples compared to those of 364-day AASHTO T259 Pseudo-Diffusion achieve a maximum R^2 value at 364 days of testing. R^2 values from correlations of Surface Resistivity and RMT tests to the references were also included in the comparison. The same trend of results is reported. Therefore, it is concluded that the best RCP testing age to predict a 364-day Bulk Diffusion test is 91 days and 364 days to predict a 364-day AASHTO T259 test.

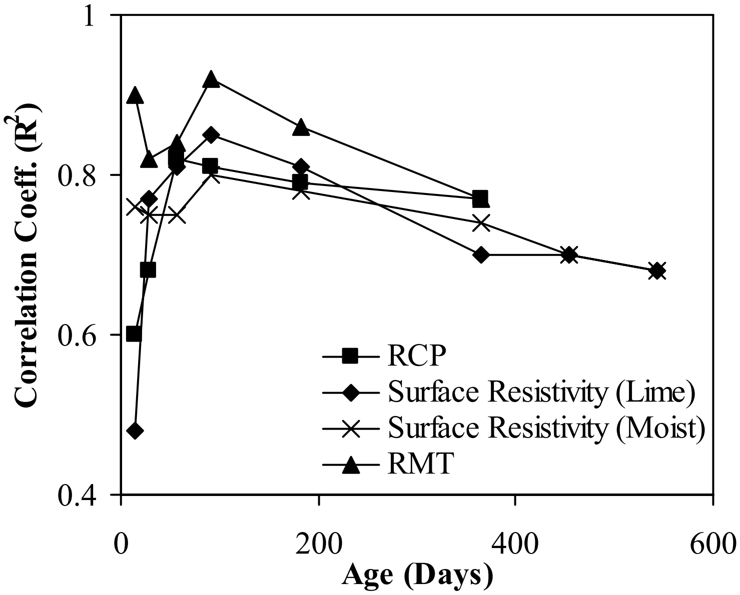


Figure 64. General Level of Agreement (R^2) of Electrical Tests by Testing Ages with 364-Day Bulk Diffusion.

The Bulk Diffusion test appears to represent a more consistent benchmark to evaluate the conductivity tests rather than the AASHTO T259 test. The chloride diffusion is better simulated by the Bulk Diffusion test, which promotes a primarily diffusion based transport of chlorides rather than the multiple mechanisms induced by the AASHTO T259 test. AASHTO T259 test set up nature includes a combined effect of diffusion, adsorption and vapor conduction (wicking) mechanisms. Moreover, correlation results to the short-term electrical tests show that the 364-day Bulk Diffusion represents a better point of reference. Hence, the short-term electrical tests reach better predictions of a long-term behavior at early ages. This represents a more practical application of the intended "short-term" procedures of predicting a realistic long-term flow of chlorides.

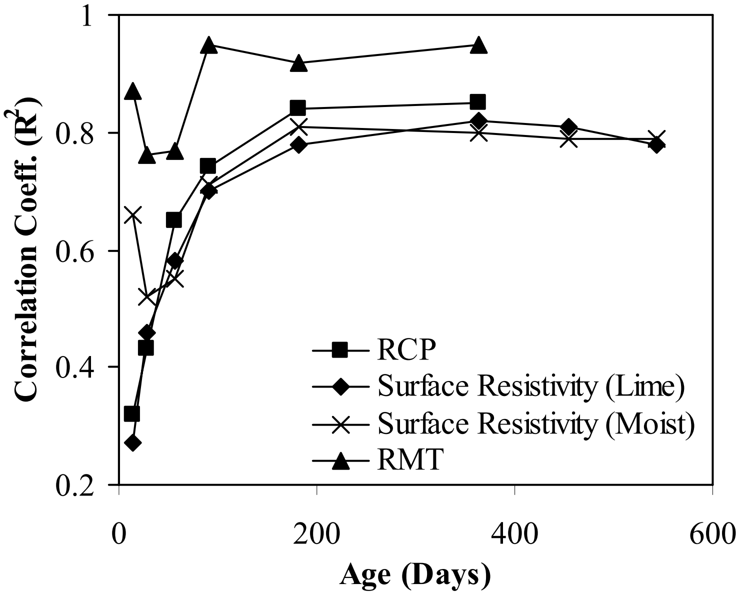


Figure 65. General Level of Agreement (R^2) of Electrical Tests by Testing Ages with 364-Day AASHTO T259 Pseudo-Diffusion.

A new calibrated scale to categorize the equivalent measured charge in coulombs to the chloride ion permeability of the concrete was calculated following Whiting's research program basis (Whiting 1981). The RCP test at 91 days was selected as the most effective testing age to predict the chloride diffusion penetration of a 364-day Bulk Diffusion test. Therefore, a more realistic diffusion coefficient associated with this test result can be derived. The diffusion coefficient related to a given coulomb value can be obtained from the trend line equation of the test correlations. Figure 66 shows the 364-day Bulk Diffusion coefficient associated with a 1000 coulombs for a 91-day RCP test. This diffusion coefficient is believed to represent a realistic interpretation of the standard 1000 coulomb's RCP limit. Table 25 proposed a scale for categorizing 91 day RCP results related to the chloride permeability measured by a 364-day Bulk Diffusion test.

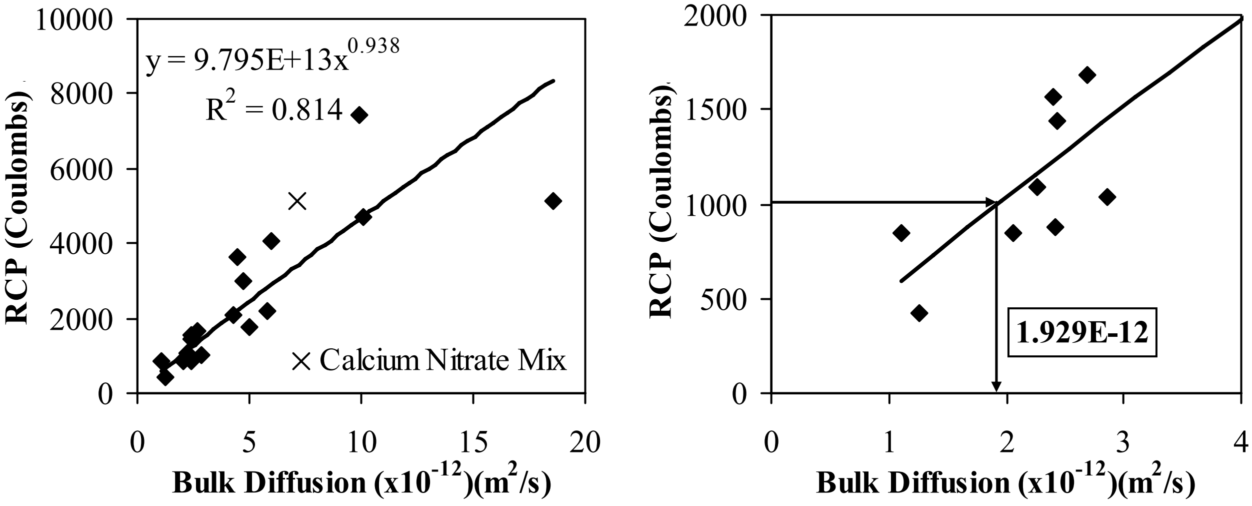


Figure 66. 364-Day Bulk Diffusion Coefficient Associated with a 91-Day RCP Test of a 1000 Coulombs.

Table 25. 364-Day Bulk Diffusion Relative to 91-Day RCP Charge Passed (Coulombs).

91-Day RCP Charge Passed (Coulombs)	**364-Day Bulk Diffusion ($\times10^{-12}$) (m^2/s)**
> 4,000	> 8.453
2,000 - 4,000	4.038 - 8.453
1,000 - 2,000	1.929 - 4.038
100 - 1,000	0.166 - 1.929
< 100	< 0.166

7 SUMMARY AND CONCLUSIONS

This report details results of a research project aimed at evaluating currently available conductivity tests and compare the results of these tests to those from long-term diffusion tests. Rapid Chloride Permeability (RCP), Rapid Migration Test (RMT), Surface Resistivity (SR), and impressed current were evaluated. The primary objective of this research was to compare the RMT and surface resistivity methods to other standard test methods for chloride penetration. Bulk Diffusion and AASHTO T259, two long-term tests, were selected as a benchmark to evaluate conductivity tests. The tests were conducted using a 364-day chloride exposure. Diffusion coefficients from Bulk Diffusion test results were determined by fitting the data obtained in the chloride profiles analysis to Fick's Diffusion Second Law equation. Two procedures were used to evaluate the data collected from the AASHTO T259 test; total integral chloride content and by fitting the data to the pure diffusion Fick's Second Law equation to obtain an apparent diffusion coefficient. The electrical results from the short-term tests RCP, SR and RMT at 14, 28, 56, 91, 182 and 364 days of age were then compared to the two long-term diffusion reference tests. Conclusions are as follows:

- It was found that total integral content results did not correlate well with that of the Bulk Diffusion coefficients (R^2 of 0.339). Comparison of the long-term diffusion coefficients gives a much better R^2 value of 0.829. Therefore, Fick's Diffusion Second Law approximation was selected as more appropriate method of analysis for AASHTO T259 method.
- Correlations between the RMT and the long-term tests were equal or slightly better than those obtained by the RCP and SR tests. RMT test is less affected by the presence of supplementary cementitious materials. The test was applicable to wider range mineral admixtures in concrete than the RCP and SR tests.
- The comparison of results of the SR tests between the two curing procedures showed no significant differences. Therefore, it is concluded that either of the methods will provide similar results.
- The colorimetric technique based on spraying silver nitrate solution to determine the chloride penetration was compared to the acid soluble chloride content method. A set of 63 samples were axially split; acid soluble chloride content was measured on one half and colorimetric penetration was determined on the other half by spraying silver nitrate solution. An average chloride concentration of 0.14% by weight of concrete at the color-change boundary was found by this evaluation. However, the reported average presents quite a high coefficient of variation of 40.3%.
- Impressed current (FM 5-522) results of conductivity and the time-to-failure were correlated with the two long-term diffusion reference tests. Electrical conductivity results correlated better than time-to-failure results to the reference tests. The ranges on level of agreement obtained were lower than the other short-term methods presented. This can be related to the fact that the scope of the impressed current test was not intended to be a predictor of long-term chloride permeability.

- The level of agreements (R^2) obtained for all the short-term tests showed that the best testing age for a RCP, SR and RMT test to predict a 364-day Bulk Diffusion test was 91 days and 364 days to predict a 364-day AASHTO T259 test.
- A calibrated scale relating the equivalent RCP measured charge in coulombs to the chloride ion permeability of the concrete was developed. The proposed scale was based on the correlation of the 91-day RCP results related to the chloride permeability measured by a 364-day Bulk Diffusion test.

8 Recommended Approach for Determining Limits of Conductivity Tests

The standardized RCP test method, ASTM C1202, is commonly required on construction project specifications for both precast and cast-in-place concrete. Pfeifer, McDonald and Krauss (1994) indicate that the engineer or owner usually select an arbitrary value of less than 1000 coulombs for concrete elements under extremely aggressive environments. This RCP coulomb limit is required by the Florida Department of Transportation (FDOT) when Class V or Class V Special concrete containing silica fume or metakaolin as a pozzolan is tested on 28 day concrete samples (FDOT 346 2004). It has been argued that a 1000 coulombs limit for a 28 day RCP test is unreasonably low. The following recommendations present a method by which rapid electrical tests can be calibrated so that, with reasonable confidence, diffusion coefficients from the 364-day bulk diffusion test can be obtained. The fundamental assumption is that the known diffusion coefficient is sufficiently low to give the desired service life with the associated concrete cover.

To maintain consistency with the original method and because this age appears to be optimal for predicting the one-year bulk diffusion, the diffusion coefficient associated with the standard 1000 coulombs limit for a 91-day test (see Table 25) was selected as the "standard" for which the allowable limits would be set when the RCP or SR test is conducted at 28 days after casting.

8.1 RCP AND BULK DIFFUSION

The coulomb limit associated with the "standard" diffusion is calculated from the trend line equation derived on the 28-day RCP correlation to the 364-day Bulk Diffusion test. A statistical study is included to ensure the validity of this new RCP limit. A confidence interval for the mean response of the test correlations was employed. This confidence interval represents the statistical probability that the next set of samples tested will fall within the specified acceptance range. The confidence interval is calculated according to the analytical derivation presented as followed:

$$\mu_{Y|xO} = y_o \pm t_\alpha . s. \sqrt{\frac{1}{n} + \frac{(x_o - \bar{x})^2}{S_{xx}}}$$

$$s = \sqrt{\frac{S_{yy} - b.S_{xy}}{n-2}}$$

$$S_{xx} = \sum_{i=1}^{n} (x_i - \bar{x})^2$$

$$S_{yy} = \sum_{i=1}^{n} (y_i - \bar{y})^2$$

$$S_{xy} = \sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})$$

where $\mu_{Y|x_O}$ is the mean confidence limit response for an independent variable x_o; y_o: dependent variable from regression analysis equation; t_α: one-tailed Student's t-distribution value with n-2 degrees of freedom for an specific confidence level; y_i: experimental dependent variables; $\bar{y}$: mean of experimental dependent variables; x_i: experimental independent variables; $\bar{x}$: mean of experimental independent variables; b: slope value from regression analysis; n: number of samples.

Figure 67 shows the 90% confidence limit for the mean response of the 28-day RCP test correlation to the 364-day Bulk Diffusion reference test. The coulomb limit for a 28-day RCP test associated with 90% confidence on the correlated data is derived as shown in Figure 68. Moreover, several coulomb limits for concrete elements under extremely aggressive environments at different levels of confidence are presented in Table 26. The RCP coulomb limits were rounded for a more practical utilization. The different levels of confidence are provided to offer some flexibility to the Florida Department of Transportation to make a final decision specifically suitable to their standards.

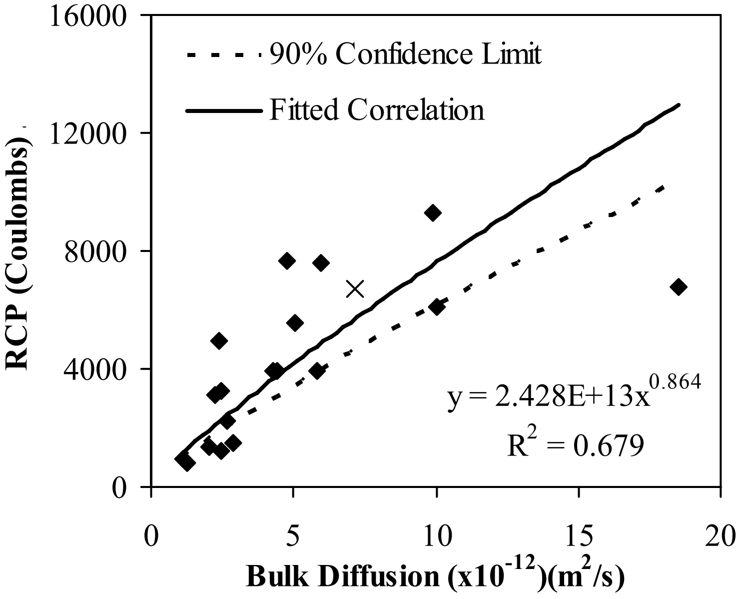


Figure 67. 90% Confidence Limit for Mean Response of 28-Day RCP Test vs. 364-Day Bulk Diffusion Test Correlation.

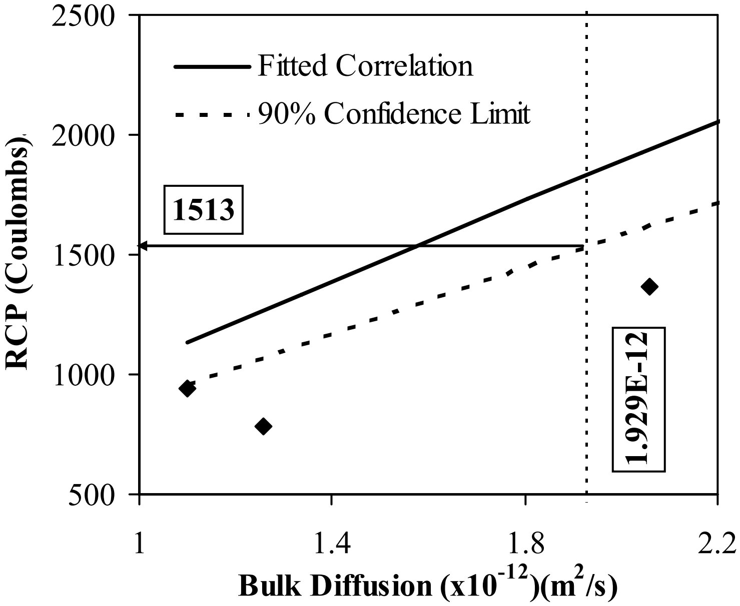


Figure 68. 28-Day RCP Coulombs Limit with a 90% Confidence Level for Concrete Elements Under Extremely Aggressive Environments (Very Low Chloride Permeability).

Table 26. Allowable RCP Values for a 28-Day Test for Concrete Elements Under Extremely Aggressive Environments (Very Low Chloride Permeability) and Associated Confidence Levels

28-Day RCP Charge Passed (Coulombs)	**28-Day RCP Charge Passed (Rounded Values) (Coulombs)**	**Confidence Level**
1,513	1,500	90%
1,426	1,400	95%
1,264	1,250	99%

It is important to recognize that the limits presented in Table 26 and in the following sections are based on the relatively limited data gathered from the laboratory specimens prepared and tested as a part of this research project. For example, consider the 90% confidence level in the table. This indicates that if a random sample is selected from the tests reported in this research that has an RCP value less than 1,513 coulombs, then, with 90% confidence, that same concrete would have a 365-day bulk diffusion coefficient that is less than 1.929E-12 m^2/s. Recall that this diffusion coefficient standard was established in the previous chapter to represent concrete that will have RCP test results of 1000 coulombs when tested at 91 days.

In addition, the recommended RCP limits are evaluated to corroborate their applicability to the standard FDOT specifications. These more flexible proposed RCP limits still need to meet the basic rating criteria of the current FDOT specification. Therefore, the recommended limits must discriminate between concrete samples that were designed as low chloride permeable and samples with higher permeability. FDOT categorizes Class V and Class V Special containing silica fume or metakaolin as a pozzolan as low permeable mixtures. The higher RCP associated with the lower confidence level showed in Table 26 is selected as the more representative limit for the evaluation. The concrete mixtures used in this research were divided into two groups. The first group included mixtures that were not design to meet FDOT standard specifications and the second group included samples designed to meet the minimum requirements. Table 27 shows the 28-day RCP pass rates by FDOT standard specifications for the two groups of samples. All the RCP coulomb results from the first group of samples exceed the current FDOT standard of 1000 coulombs as well as the limit of 1500 coulombs. In the second group, less than half of the samples passed the current FDOT RCP limit.

Data from field mixtures were also used to evaluate various RCP limits (Chini, Muszynski, and Hicks 2003). Data from the 491 samples collected on construction projects were included in the analysis (see Table 27). The samples were collected from actual job sites of concrete pours in the state of Florida.

Table 27. 28-Day RCP Pass Rates of Several Concrete Samples by FDOT Standard Specifications (FDOT 346 2004).

		28-Day RCP Limits (Coulombs)							
		Without Silica Fume or MK(3)				**With Silica Fume or MK(3)**			
		1000	**1250**	**1400**	**1500**	**1000**	**1250**	**1400**	**1500**
Current Research	**Total Number of Mixtures**	14	14	14	14	5(1)	5(1)	5(1)	5(1)
	Number of Passed Mixtures	0	0	0	0	2	3	4	5
	Percentage of Passed Mixtures	0%	0%	0%	0%	40%	60%	80%	100%
Chini, Muszynski, and Hicks 2003	**Total Number of Mixtures (2)**	455	455	455	455	36	36	36	36
	Number of Passed Mixtures	4	12	18	25	15	20	23	23
	Percentage of Passed Mixtures	<1%	2.6%	4%	5.5%	42%	56%	64%	64%

(1) All Mixtures were cast at the FDOT laboratory.
(2) All Mixtures were collected from actual job sites.
(3) Metakaolin.

The diffusion coefficients presented in Table 25 were also used to derive the entire equivalent charges in coulombs for the different chloride permeability ranges. The allowable coulomb limits for a 28-day RCP test response with a 90% of confidence on the correlated data are derived in Figure 69 to Figure 71. Coulomb limits for concrete elements with different chloride permeability at different levels of confidence are summarized in Table 28 to Table 30. Moreover, the RCP coulomb limits were rounded for a more practical utilization.

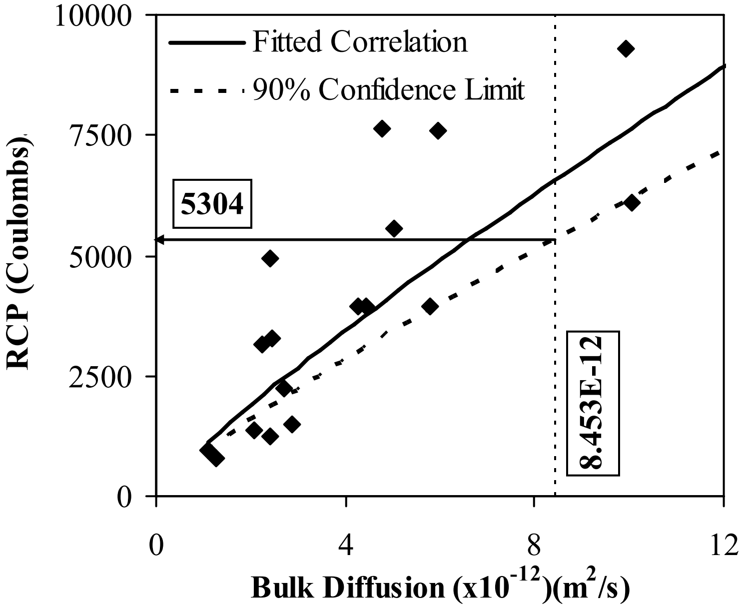


Figure 69. 28-Day RCP Coulombs Limit with a 90% Confidence Level for Concrete Elements with a Moderate Chloride Permeability.

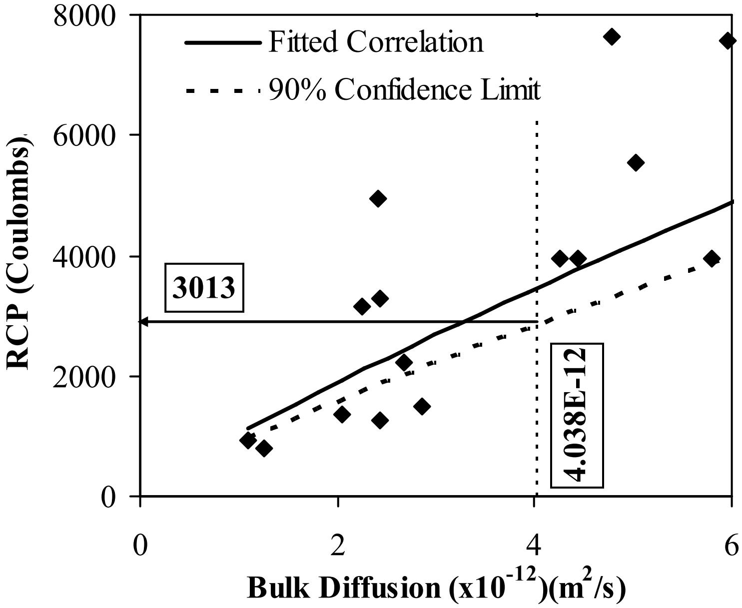


Figure 70. 28-Day RCP Coulombs Limit with a 90% Confidence Level for Concrete Elements with a Low Chloride Permeability.

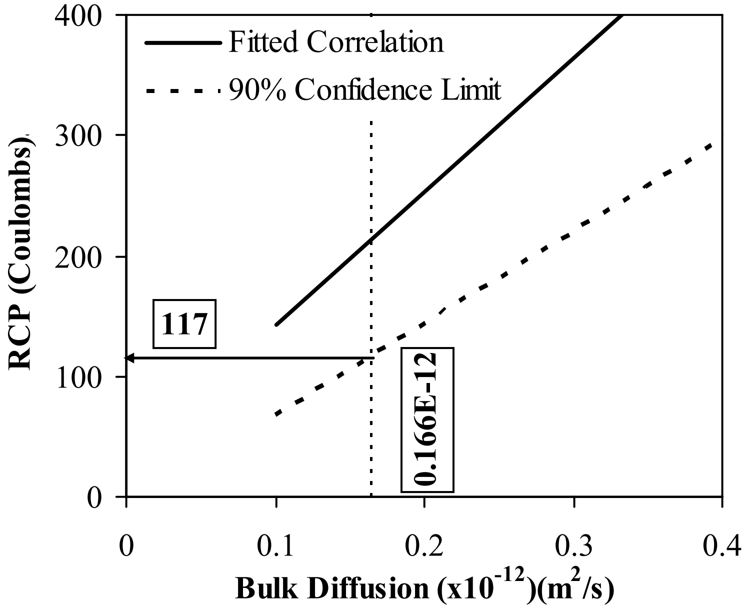


Figure 71. 28-Day RCP Coulombs Limit with a 90% Confidence Level for Concrete Elements with a Negligible Chloride Permeability.

Table 28. Allowable RCP Values for a 28-Day Test with a 90% Confidence Levels for Concrete Elements with Different Chloride Permeability.

AASHTO T277 Standard Limits		**Current Research Allowable RCP Limits 90% Confidence Level**		
			28-Day RCP	
Chloride Permeability	**91-Day RCP Charge Passed (Coulombs)**	**364-Day Bulk Diffusion (x10^{-12}) (m^2/s)**	**Charge Passed (Coulombs)**	**Charge Passed (Rounded Values) (Coulombs)**
High	> 4,000	> 8.453	> 5,304	> 5,300
Moderate	2,000-4,000	4.038 - 8.453	3,013-5,304	3,000-5,300
Low	1,000-2,000	1.929 - 4.038	1,513-3,013	1,500-3,000
Very Low	100-1,000	0.166 - 1.929	117-1,513	110-1,500
Negligible	< 100	< 0.166	< 117	< 110

Table 29. Allowable RCP Values for a 28-Day Test with a 95% Confidence Levels for Concrete Elements with Different Chloride Permeability.

AASHTO T277 Standard Limits		**Current Research Allowable RCP Limits 95% Confidence Level**		
			28-Day RCP	
Chloride Permeability	**91-Day RCP Charge Passed (Coulombs)**	**364-Day Bulk Diffusion ($x10^{-12}$) (m^2/s)**	**Charge Passed (Coulombs)**	**Charge Passed (Rounded Values) (Coulombs)**
High	> 4,000	> 8.453	> 4,966	> 4,900
Moderate	2,000-4,000	4.038 - 8.453	2,885-4,966	2,800-4,900
Low	1,000-2,000	1.929 - 4.038	1,426-2,885	1,400-2,800
Very Low	100-1,000	0.166 - 1.929	96-1,426	90-1,400
Negligible	< 100	< 0.166	< 96	< 90

Table 30. Allowable RCP Values for a 28-Day Test with a 99% Confidence Levels for Concrete Elements with Different Chloride Permeability.

AASHTO T277 Standard Limits		**Current Research Allowable RCP Limits 99% Confidence Level**		
			28-Day RCP	
Chloride Permeability	**91-Day RCP Charge Passed (Coulombs)**	**364-Day Bulk Diffusion ($x10^{-12}$) (m^2/s)**	**Charge Passed (Coulombs)**	**Charge Passed (Rounded Values) (Coulombs)**
High	> 4,000	> 8.453	> 4,340	> 4,300
Moderate	2,000-4,000	4.038 - 8.453	2,639-4,340	2,600-4,300
Low	1,000-2,000	1.929 - 4.038	1,264-2,639	1,200-2,600
Very Low	100-1,000	0.166 - 1.929	65-1,264	60-1,200
Negligible	< 100	< 0.166	< 65	< 60

8.2 SR AND BULK DIFFUSION

Chini, Muszynski and Hicks (2003) evaluated the possible replacement of the widely used electrical RCP test (AASHTO T277, ASTM C1202) by the simple non-destructive Surface Resistivity test. A permeability rating table to aid the categorization of the equivalent Surface Resistivity results to the chloride permeability of the concrete was proposed (see Table 6). A minimum resistivity value of 37 KOhm-cm was reported to represent concrete with low chloride ion permeability. However, the permeability interpretation of the Surface Resistivity test results was entirely based on correlations to the previous ranges provided in the standard RCP test (see Table 1). As it was indicated in the previous section, incorrect interpretation of electrical test results can be made when relying entirely on these RCP standard ranges. Therefore, a more rational approach to setting the limits of the Surface Resistivity results is needed.

The Surface Resistivity test was conducted using two methods of curing, one at 100% humidity (moist cured) and the other in a saturated $Ca(OH)_2$ solution (lime cured). It was previously concluded that either of the methods will derive an equal resistivity behavior. Consequently, Surface Resistivity results from the most commonly used curing method, moist cured, are used in this section. The long-term diffusion coefficient derived in the previous section is also used as a benchmark for the interpretation of the Surface Resistivity results (see Table 25). This coefficient is believed to represent a realistic interpretation of low chloride permeability concrete. The 28-day Surface Resistivity limit associated with the standard diffusion is calculated from the trend line equation of correlation to the reference test. A statistical study is included to ensure the validity of this new Surface Resistivity limit. A confidence interval for the mean response of the test correlations was included. Figure 72 shows the 90% confidence interval for the mean response of the 28-day Surface Resistivity test correlation to the 364-day Bulk Diffusion reference test. The allowable 28-day Surface Resistivity limit with a 90% of confidence on the correlated data is derived in Figure 73. Moreover, several Surface Resistivity limits for concrete elements under extremely aggressive environments at different levels of confidence are presented in Table 31. The limits were rounded for a more practical utilization. The different levels of confidence are provided to offer some flexibility to the Florida Department of Transportation to make a final decision specifically suitable to their standards.

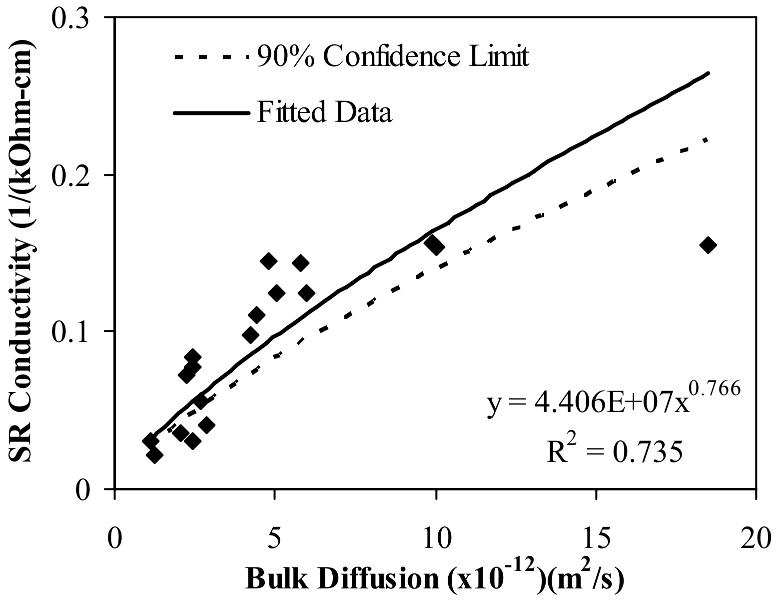


Figure 72. 90% Confidence Limit for Mean Response of 28-Day Surface Resistivity Test (Moist Cured) vs. 364-Day Bulk Diffusion Test Correlation.

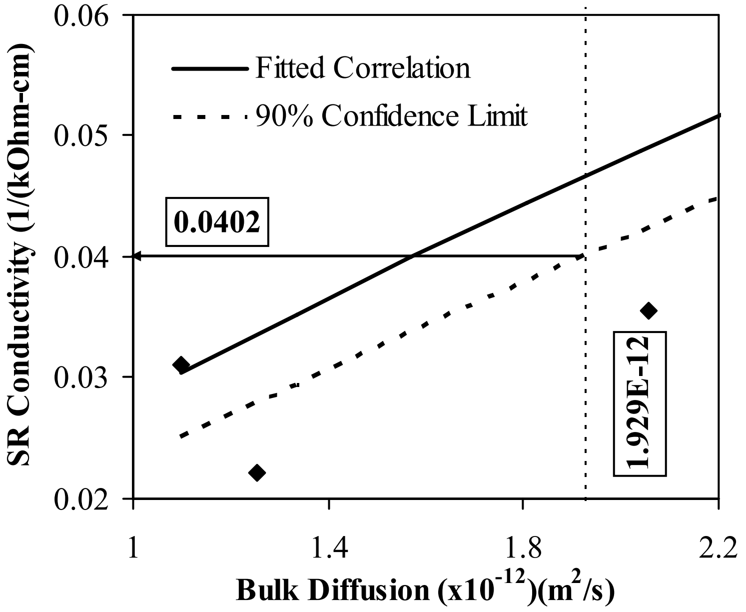


Figure 73. 28-Day Surface Resistivity (Moist Cured) Limit with a 90% Confidence Level for Concrete Elements Under Extremely Aggressive Environments (Very Low Chloride Permeability).

Table 31. Allowable Surface Resistivity Values for a 28-Day Test for Concrete Elements Under Extremely Aggressive Environments.

28-Day Surface Resistivity (Moist Cured)			
Conductivity (1/(kOhm-cm))	**Resistivity (kOhm-cm)**	**Resistivity (Rounded Values) (kOhm-cm)**	**Confidence Level**
0.0402	24.85	25	90%
0.0384	26.01	26	95%
0.0350	28.57	29	99%

Additionally, the recommended Surface Resistivity limits are evaluated to corroborate their applicability to evaluate low chloride permeability concrete. A low chloride permeability concrete is assumed as the FDOT standard to be a Class V or Class V Special concrete containing silica fume or metakaolin as a pozzolan. Similar analysis as shown in Table 27 for the RCP limits evaluation is presented. The lower resistivity limit associated with the lower confidence level (see Table 31) is selected as the more representative for the evaluation. Furthermore, Surface Resistivity results reported by Chini, Muszynski and Hicks (2003) research are also included in the validation (see Table 32).

Table 32. 28-Day Surface Resistivity Pass Rates of Several Concrete Samples by FDOT Standard Specifications (FDOT 346 2004).

		28-Day Surface Resistivity Limits (KOhm-cm)							
		Without Silica Fume or MK(3)				**With Silica Fume or MK(3)**			
		37	**29**	**26**	**25**	**37**	**29**	**26**	**25**
Current Research	**Total Number of Mixtures**	14	14	14	14	5(1)	5(1)	5(1)	5(1)
	Number of Passed Mixtures	0	0	0	0	1	3	4	4
	Percentage of Passed Mixtures	0%	0%	0%	0%	20%	60%	80%	80%
Chini, Muszynski, and Hicks 2003	**Total Number of Mixtures (2)**	462	462	462	462	40	40	40	40
	Number of Passed Mixtures	7	20	36	46	8	18	24	25
	Percentage of Passed Mixtures	1.5%	4.3%	7.8%	10%	20%	45%	60%	63%

(1) All Mixtures were cast at the FDOT laboratory.
(2) All Mixtures were collected from actual job sites.
(3) Metakaolin.

The diffusion coefficients presented in Table 25 were also used to derive the entire equivalent surface resistivity limits for the different chloride permeability ranges. The allowable surface resistivity limits for a 28-day SR test response with a 90% of confidence on the correlated data are derived in Figure 74 to Figure 76. Resistivity limits for concrete elements with different chloride permeability at different levels of confidence are summarized in Table 33 to Table 35. Moreover, the surface resistivity limits were rounded for a more practical utilization.

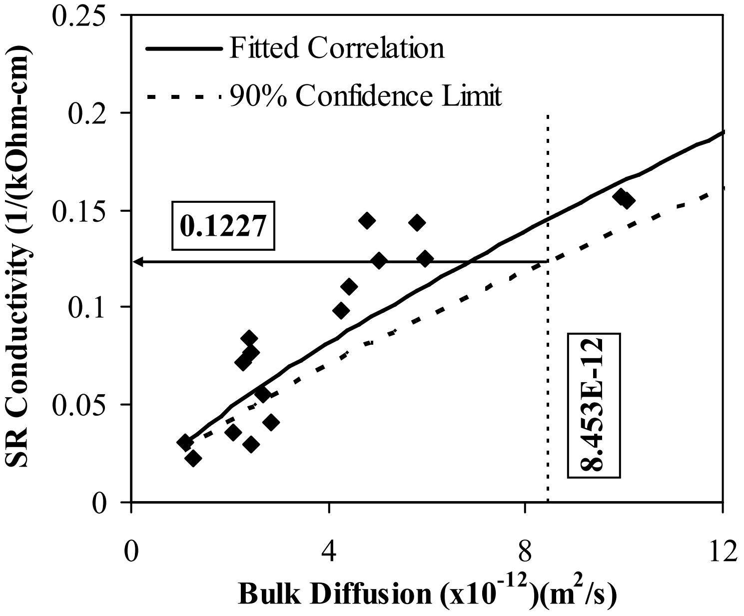


Figure 74. 28-Day Surface Resistivity (Moist Cured) Limit with a 90% Confidence Level for Concrete Elements with a Moderate Chloride Permeability.

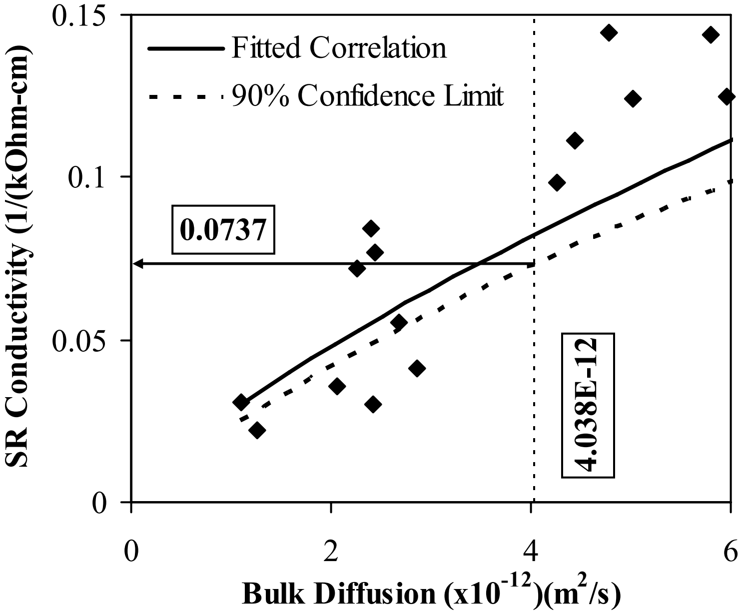


Figure 75. 28-Day Surface Resistivity (Moist Cured) Limit with a 90% Confidence Level for Concrete Elements with a Low Chloride Permeability.

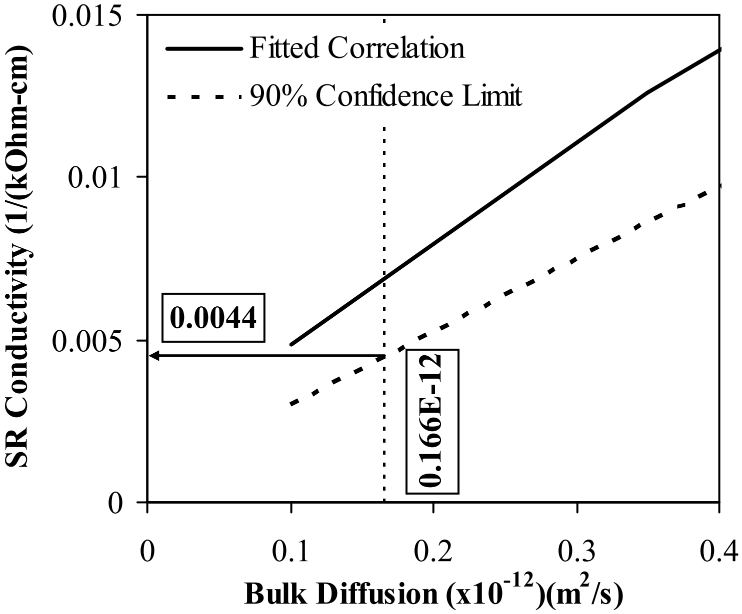


Figure 76. 28-Day Surface Resistivity (Moist Cured) Limit with a 90% Confidence Level for Concrete Elements with a Negligible Chloride Permeability.

Table 33. Allowable Surface Resistivity (Moist Cured) Values for a 28-Day Test with a 90% Confidence Levels for Concrete Elements with Different Chloride Permeability.

AASHTO T277 Standard Limits		**Current Research Allowable SR Limits 90% Confidence Level**			
			28-Day Surface Resistivity		
Chloride Permeability	**91-Day RCP Charge Passed (Coulombs)**	**364-Day Bulk Diffusion $(\times 10^{-12})$ (m^2/s)**	**Conductivity (1/(kOhm-cm))**	**Resistivity (kOhm-cm)**	**Resistivity (Rounded Values) (kOhm-cm)**
High	> 4,000	> 8.453	> 0.1227	< 8.15	< 8
Moderate	2,000-4,000	4.038 - 8.453	0.0737-0.1227	8.15-13.57	8-14
Low	1,000-2,000	1.929 - 4.038	0.0402-0.0737	13.57-24.85	14-25
Very Low	100-1,000	0.166 - 1.929	0.0044-0.0402	24.85-229.3	25-229
Negligible	< 100	< 0.166	< 0.0044	> 229.3	> 229

Table 34. Allowable Surface Resistivity (Moist Cured) Values for a 28-Day Test with a 95% Confidence Levels for Concrete Elements with Different Chloride Permeability.

AASHTO T277 Standard Limits		**Current Research Allowable SR Limits 95% Confidence Level**			
			28-Day Surface Resistivity		
Chloride Permeability	**91-Day RCP Charge Passed (Coulombs)**	**364-Day Bulk Diffusion ($x10^{-12}$) (m^2/s)**	**Conductivity (1/(kOhm-cm))**	**Resistivity (kOhm-cm)**	**Resistivity (Rounded Values) (kOhm-cm)**
High	> 4,000	> 8.453	> 0.1166	< 8.58	< 9
Moderate	2,000-4,000	4.038 - 8.453	0.0713-0.1166	8.58-14.03	9-14
Low	1,000-2,000	1.929 - 4.038	0.0384-0.0713	14.03-26.01	14-26
Very Low	100-1,000	0.166 - 1.929	0.0038-0.0384	26.01-266.4	26-266
Negligible	< 100	< 0.166	< 0.0038	> 266.4	> 266

Table 35. Allowable Surface Resistivity (Moist Cured) Values for a 28-Day Test with a 99% Confidence Levels for Concrete Elements with Different Chloride Permeability.

AASHTO T277 Standard Limits		**Current Research Allowable SR Limits 99% Confidence Level**			
			28-Day Surface Resistivity		
Chloride Permeability	**91-Day RCP Charge Passed (Coulombs)**	**364-Day Bulk Diffusion ($x10^{-12}$) (m^2/s)**	**Conductivity (1/(kOhm-cm))**	**Resistivity (kOhm-cm)**	**Resistivity (Rounded Values) (kOhm-cm)**
High	> 4,000	> 8.453	> 0.1050	< 9.52	< 10
Moderate	2,000-4,000	4.038 - 8.453	0.0665-0.1050	9.52-15.04	10-15
Low	1,000-2,000	1.929 - 4.038	0.0350-0.0665	15.04-28.57	15-29
Very Low	100-1,000	0.166 - 1.929	0.0028-0.0350	28.57-362.5	29-363
Negligible	< 100	< 0.166	< 0.0028	> 362.5	> 363

9 FIELD CORE SAMPLING

9.1 *BRIDGE SELECTION*

In previous chapters results from laboratory test procedures such as Bulk Diffusion and AASHTO T259 were used to estimate the long-term chloride diffusion performance of concrete. These tests were conducted using a 364-day chloride exposure. Longer term diffusion test results are needed to confirm the laboratory findings presented in earlier chapters. To provide additional data to which laboratory results can be corroborated, several concrete specimens were collected from FDOT bridges located in marine environments.

Recently constructed bridges (since 1991) were surveyed. The search criteria included bridges in which the structural elements were originally designed to meet the FDOT specifications (FDOT 346 2004) for concrete elements under extremely aggressive environments. The mixture designs for the selected structural elements used silica fume as a pozzolan for a FDOT class V or class V special mixture. The search criteria also included mixtures for which RCP data were available (see Table 39). This information allowed a direct comparison with the laboratory results reported in previous sections. Six bridges had substructures that met these requirements (see Table 36, Table 37 and Table 38).

The intent of the sampling was to take concrete cores from undamaged concrete near the tide lines. The cores were then sliced or ground and chloride content was measured to produce a profile, from which the diffusion coefficient was calculated.

Table 36. FDOT Cored Bridge Structures for the Investigation.

Bridge Name	Abbr.	County (District)	Location	Bridge #	Project #	Year Built
Hurricane Pass	HPB	Lee (D1)	SR-865 San Carlos Blvd	120089	12004-3506	1980/91(*)
Broadway Replacement East Bound	BRB	Volusia (D5)	US-92 E International Speedway Blvd.	790187	79080-3544	2001
Seabreeze West Bound	SWB	Volusia (D5)	SR-430	790174	79220-3510	1997
Granada	GRB	Volusia (D5)	SR-40 Granada Blvd.	790132	79150-3515	1983/97(*)
Turkey Creek	TCB	Brevard (D5)	US-1	700203	70010-3529	1999
New Roosevelt	NRB	Martin (D4)	US-1/SR-5	890152	(**)	1997

(*) Built year/Modified year
(**) Unknown Information

Table 37. FDOT Cored Bridge Element Mixture Designs.

Materials	**Bridge Name Abbreviation**					
	HPB	**BRB**	**SWB**	**GRB**	**TCB**	**NRB**
	Class V	Class V	Class V	Class V Special	Class V Special	Class (*)
	Lee (D1)	Volusia (D5)	Volusia (D5)	Volusia (D5)	Brevard (D5)	Martin (D4)
FDOT Mixture #	3514	05-M2028	05-0446	05-0426	07-M0223B	(*)
W/C	0.35	0.33	0.35	0.35	0.33	(*)
Cement(pcy)	617	605	595	618	785	(*)
Pozzolan 1 (pcy)	Fly-Ash (19.5%) 135	Fly-Ash (19.5%) 168	Fly-Ash (18%) 145	Fly-Ash (18%) 150	Fly-Ash (18%) 192	(*)
Pozzolan 2 (pcy)	Silica Fume (10.3%) 87	Silica Fume (10.3%) 89	Silica Fume (7.8%) 63	Silica Fume (8.3%) 70	Silica Fume (8.1%) 86	(*)
Water (pcy)	263	219	271.6	292	355	(*)
Fine Aggregate (pcy)	1,111	912	1,055	1,314	1,281	(*)
Coarse Aggregate (pcy)	1,616	1,925	1,784	1,475	2,286	(*)
Air Entrainer (oz)	7	8.4	10	6.8	9.2	(*)
Water Reducer (oz)	30.85	42	17.9	30.9	31.4	(*)
Super Plasticizer (oz)	56	134	95.2	185.4	98.1	(*)

(*) Unknown Information

Table 38. FDOT Cored Bridge Element Mixture Material Sources.

	Bridge Name Abbreviation					
	HPB	**BRB**	**SWB**	**GRB**	**TCB**	**NRB**
Portland Cement	Florida Mining & Materials AASHTO M-85 Type II	Pennsuco Tarmac AASHTO M-85 Type II	BROCO (Brooksville) AASHTO M-85 Type II	BROCO (Brooksville) AASHTO M-85 Type II	BROCO (Brooksville) AASHTO M-85 Type II	(*)
Fly-Ash	Florida Mining & Materials Class F	Boral Bowen Class F	Florida Mining & Materials Class F	MONEX Crystal River Class F	Florida Fly Ash Class F	(*)
Silica Fume	W.R. GRACE DARACEM 10,000	Master Builders MB-SF 110	W.R. GRACE DARACEM 10,000D	Master Builders RHEOMAC SF 100	W.R. GRACE DARACEM 10,000D	(*)
Water	Port Manatee, FL	Dayton Beach, FL	Orlando, FL	West Palm Beach, FL	Tampa, FL	(*)
Fine Aggregate	Florida Crushed Stone Silica Sand	Florida Rock Ind. Silica Sand	Florida Rock Ind. Silica Sand	Florida Rock (Marison) Silica Sand	Vulca/ICA Silica Sand	(*)
Coarse Aggregate	Florida Crushed Stone Crushed Limestone	Martin Marietta Aggregates Crushed Granite	Martin Marietta Aggregates Crushed Granite	Martin Marietta Aggregates Crushed Granite	Florida Crushed Stone Crushed Limestone	(*)
Air Entrainer	W.R. GRACE Daravair 79	Master Builders MBAE 90	W.R. GRACE DAREX	Master Builders MBVR-S	W.R. GRACE Daravair 79	(*)
Water Reducer	W.R. GRACE WRDA	Master Builders POZZ.200N	W.R. GRACE WRDA 64	Master Builders LL961R	W.R. GRACE WRDA	(*)
Super Plasticizer	W.R. GRACE WRDA 19	Master Builders RHEO 1,000	W.R. GRACE DARACEM 100	Master Builders RHEO 1,000	W.R. GRACE WRDA 19	(*)

(*) Unknown Information

Table 39. 28-Day RCP Test Data from Concrete Mixture Designs of the Cored Samples.

Bridge Name	28-Day RCP (Coulombs)
Hurricane Pass	(*)
Broadway Replacement East Bound	952
Seabreeze West Bound	700
Granada	538
Turkey Creek	(*)
New Roosevelt	(*)

(*) Data unavailable

9.2 CORING PROCEDURES

A total of 14 core samples were obtained from the substructures of the six selected bridges. Figure 77 through Figure 88 show a general view of the bridge structures and the cored substructure elements. Concrete cores were extracted from the substructure elements in the tidal region between the high tide line (HTL) and the organic tide line (OTL) (see Figure 89). HTL was determined visually by the oil or scum stain on the structural element. OTL was also identified visually as the elevation that appeared to have continuous marine growth present such as barnacles or other growth. This line is usually lower than the HTL and represents a tide level that is regularly inundated providing a regular source of water to support the marine growth and to keep the concrete saturated. The location of the extracted cores was measured from HTL and OTL to the sample center. Core elevations ranged from 3-inch (76-mm) to 12-inch (305-mm) below HTL and 3-inch (76-mm) to 10-inch (254-mm) above OTL. Table 40 shows a summary of the location, date, and time the cores were extracted.

Figure 77. Hurricane Pass Bridge (HPB) General Span View.

Figure 78. Hurricane Pass Bridge (HPB) Substructure Elements.

Figure 79. Broadway Replacement East Bound Bridge (BRB) General Span View.

Figure 80. Broadway Replacement East Bound Bridge (BRB) Substructure Elements.

Figure 81. Seabreeze West Bound Bridge (SWB) General Span View.

Figure 82. Seabreeze West Bound Bridge (SWB) Substructure Elements.

Figure 83. Granada Bridge (GRB) General Span View.

(a) (b)

Figure 84. Granada Bridge (GRB) Substructure Elements. a) Pier Elements, b) Barge Crashwall.

Figure 85. Turkey Creek Bridge (TCB) General Span View.

Figure 86. Turkey Creek Bridge (TCB) Substructure Elements.

Figure 87. New Roosevelt (NRB) General Span View.

Figure 88. New Roosevelt (NRB) Substructure Elements.

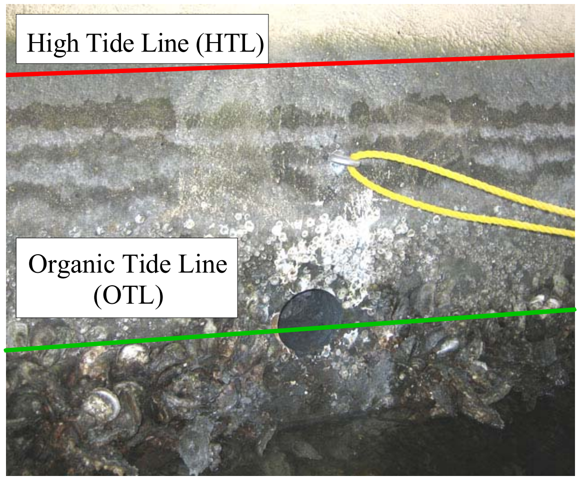


Figure 89. Cored Element Location Defined by the Water Tide Region between High Tine Line (HTL) and the Organic Tide Line (OTL). Sample from Broadway Replacement East Bound Bridge (BRB) (East Bound) BENT 11, PIER 1.

Table 40. Summary of Cores Extracted and Associated Properties.

Bridge Abbr.	Lab. #	Date Cored	Structural Element	Type[(a)]	Bent #[(b)]	Pier #[(b)]	Struct. Cored Side	Elevation Below HTL (in)	Elevation Above OTL (in)
HPB	5016	2-1-06	Pile	PC	3	1	NW	3	3
	5017	2-1-06	Pile	PC	7	1	NW	6	0
	5018	2-1-06	Pile	PC	6	1	NW	6	0
BRB	5054	3-2-06	Column	CIP	11	1	SW	12	0
	5081	5-3-06	Column	CIP	7	1	NE	4	8
SWB	5082	5-3-06	Column	CIP	3	1	NE	8	8
	5083	5-3-06	Column	CIP	7	1	SW	5	10
GRB	5084	5-3-06	Crashwall	CIP	9	1	NW	6	8
TCB	5078	5-24-06	Pile	PC	3	15	NE	4	10
	5079	5-24-06	Pile	PC	4	15	NE	9	6
	5080	5-24-06	Pile	PC	5	15	NE	9	6
NRB	5075	6-1-06	Pile Cap	CIP	8	1	S	7	6
	5076	6-1-06	Pile Cap	CIP	10	1	S	6	7
	5077	6-1-06	Pile Cap	CIP	7	1	S	6	7

(a) CIP: Cast in Place and PC: Pretensioned Concrete.

(b) Bent# and Pier# were labeled in ascendant number from North to South or West to East direction depending on the bridge location. The Bent# 1 is considered as the bridge abutment.

A rebar locator was used to measure the depth of cover and bar spacing in the structural members (see Figure 90a). Due to high variability, however, the coring bit rarely reached the reinforcement during the drilling process (see Figure 91b). The samples were cored with a cylindrical 4-inch (102-mm) diameter core drill bit, resulting in a core diameter of 3-3/4-inch (95-mm) (see Figure 90b). The specimens were cored using a fresh-water bit-cooling system. After the desired depth was reached, the cores were extracted as shown in Figure 91a. The structural members were then repaired using a high bond strength mortar containing silica fume. The mortar material was applied and compacted in several layers as is shown in Figure 92.

(a) *(b)*

Figure 90. Bridge Coring Process. a) Locating Reinforcing Steel, b) Locating Drill for Coring.

(a) *(b)*

Figure 91.Obtaining Cored Sample. a) Extracting Drilled Core, b) Location of the Extracted Core that Reached Prestressing Strand.

(a) *(b)*

Figure 92. Repairing Structural Cored Member. a) Patching Cored Opening b) Finished Pier Member.

9.3 Chloride Ion Content Analysis

The obtained core samples were profiled at varying depths to obtain their respective acid-soluble chloride content in accordance with the FDOT standard test method FM 5-516 (see APPENDIX D). The core surface was first cleaned to remove barnacles or other debris. Two methods were used to obtain the respective profile samples. The top 0.48-inch (12-mm) was profiled using a milling machine. Powder samples were taken at increments of 0.08-inch (2-mm) (see Figure 93). Subsequent profiles were obtained by cutting the sample into 0.25-inch (6.5-mm) thick slices using a water-cooled diamond saw. The core profiling scheme summary is presented in Table 41. The sample obtained from the two profiling methods was pulverized and placed in plastic bags until the chloride content testing was executed. The initial chloride background levels of cored samples were determined from the deepest section of the specimens (see APPENDIX D), assuming that chlorides have not yet reached this depth.

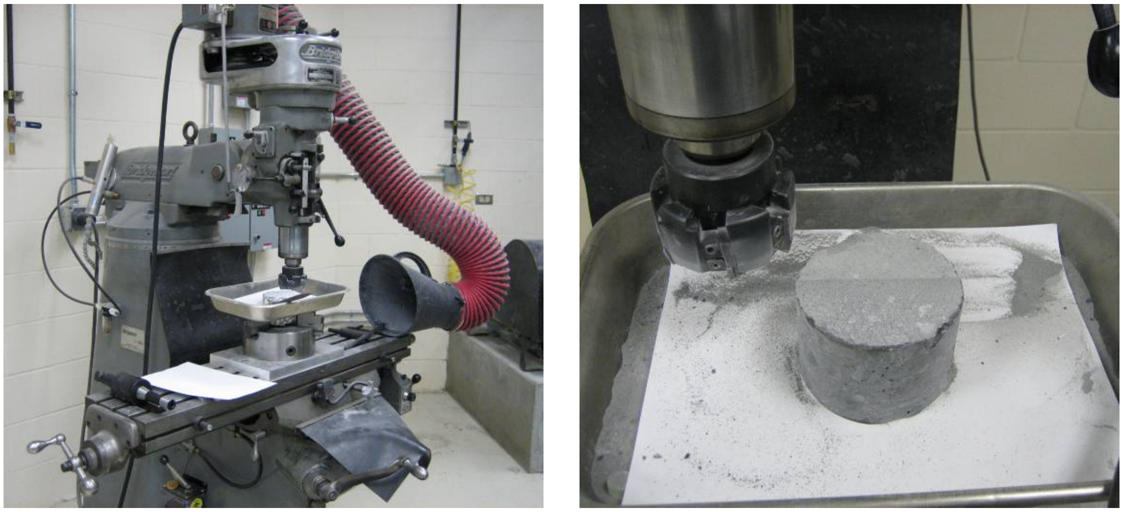

(a) (b)

Figure 93. Profile Grinding Using a Milling Machine. a) Milling Machine Set Up, b) Milling Process.

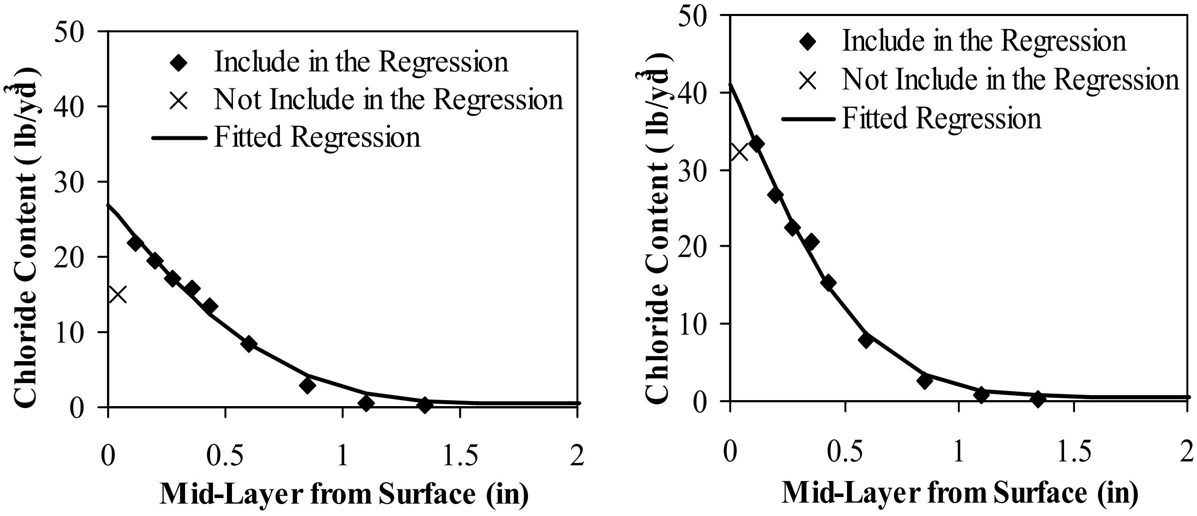
Table 41. Core Profiling Scheme.

Core Sample Identification	Profile Penetration (mm)	Profiling Method
A	0 – 2	Milling
B	2 – 4	Milling
C	4 – 6	Milling
D	6 – 8	Milling
E	8 – 10	Milling
F	10 – 12	Milling
G	12 – 18.35	Slicing
H	18.35 – 24.70	Slicing
I	24.70 – 31.05	Slicing
J	31.05 – 37.40	Slicing

9.4 RESULTS AND DISCUSSIONS

9.4.1 DIFFUSION COEFFICIENTS OF CORED SAMPLES

The chloride diffusion coefficients and surface chloride concentrations of the cored samples were obtained by fitting the obtained concentrations at varying depths and the initial chloride background levels to the non-linear Fick’s Second Law of Diffusion solution (see Table 42). The Fick’s Second Law solution assumes that the unique chloride mechanism that transports the chloride ions through the concrete is diffusion. This is a reasonable assumption for tests conducted under controlled laboratory conditions, such as the Bulk Diffusion test. Elements located in marine environments, however, are intermittently subjected to chloride exposure due to tidal fluctuations. Wetting and drying due to tides encourages absorption, which is generated by capillary suction of the concrete pulling seawater into the concrete. Moreover, the tidal fluctuations also induce leaching of unbonded shallow surface chlorides. During concrete drying period, shallow surface water evaporates and chlorides are left either as chemically bonded to the pore walls or as unbonded crystal forms. Subsequently, when the concrete is again wetted, some of these unbonded crystals are leached out of the concrete surface. Therefore, chloride profiles of field cores can differ from that obtained under permanent chloride immersion, such as the laboratory test Bulk Diffusion. The chloride concentration near the exposed surface can be considerably less than deeper into the concrete. However, previous research (Sagüés et al. 2001) has shown that diffusion coefficients can be approximately calculated by fitting the Fick's Second Law of Diffusion solution by excluding these misleading peaks in the regression analysis. The consequent chloride profile penetrations, following the initial surface values affected by leaching and absorption, fit the "pure diffusion" trend behavior. Figure 94 shows some of the diffusion coefficient regression analysis of the bridge cored samples. Diffusion analyses for each of the cored sample are summarized in APPENDIX D.



(a) *(b)*

Figure 94. Diffusion Regression Analysis for Cored Samples: (a) NRB (Lab #5075) and (b) HPB (Lab# 5017).

Table 42. Chloride Concentration Data and Calculated Diffusion Parameters.

Bridge Name	**Lab. #**	**Exposure (Years)**	**Initial Chloride Content (lb/yd^3)**	**Surface Chloride Content (lb/yd^3)**	**Diffusion Coefficient ($x10^{-12}$) (m^2/sec)**	**Water Chloride Content (ppm)**
Hurricane Pass (HPB)	**5016**	15	0.547[(a)]	20.336	0.050	19284
	5017		0.533	41.112	0.149	
	5018		0.561	44.904	0.151	
Broadway Replacement (BRB)	**5054**	5	0.467	33.012	0.585	14864[(c)]
	5081		0.858[(b)]	32.401	0.358	
Seabreeze West Bound (SWB)	**5082**	9	0.467	42.497	0.628	14864[(c)]
	5083		0.432	49.660	0.329	
Granada (GRB)	**5084**	9	0.637	0.942	0.051	14864[(c)]
Turkey Creek (TCB)	**5078**	7	0.556	26.791	0.185	9608
	5079		0.423	30.269	0.132	
	5080		0.417	33.237	0.155	
New Roosevelt (NRB)	**5075**	9	0.614	27.046	0.361	31072
	5076		0.432	28.700	0.540	
	5077		0.382	29.696	0.373	

(a) Initial Chlorides were not tested for this sample. An average between Lab sample# 5017 and 5018 was reported.

(b) Initial Chloride value was considered an erroneous value (too high). The value of initial chlorides from Lab sample# 5054 was used.

(c) The Bridge Structures are exposed to the same body of water.

The chloride profile obtained from the Granada crash wall (see Figure 95) was initially puzzling. The flat trend of chloride ingress showing chloride levels barely above background levels indicated little chloride penetration. This low penetration was likely caused by the epoxy coating applied to the surface of the structural elements (see Figure 84b).

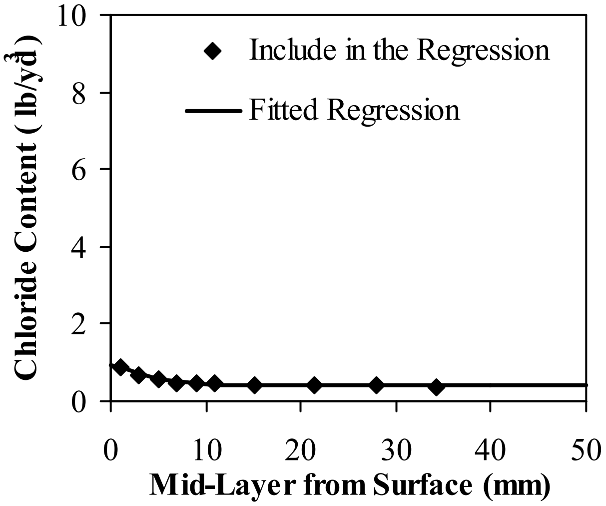


Figure 95. Diffusion Regression Analysis for Cored Sample GRB (Lab #5084).

9.4.2 CORRELATION OF LONG-TERM FIELD DATA TO LABORATORY TEST PROCEDURES

The true aim of both the short and long-term chloride exposure testing is to capture the ability of the concrete in the field to resist chloride intrusion. As the chloride concentration builds up in a concrete member, it approaches the chloride threshold, which is the point at which the reinforcement begins to corrode. The longer the chloride penetration is delayed, the longer the service life of the structure. Unfortunately, the exposure conditions in the field are quite varied and do not really match those of the standard short or long term laboratory tests that have been discussed thus far. Some of the factors include chloride concentration of solution, absolute and variation in temperature, humidity, and age of concrete among others. Additionally, mechanisms other than diffusion contribute to the intrusion of chlorides. Nevertheless, it is common to take cores of field concrete, determine chloride concentration at varying depths and calculate a chloride diffusion coefficient.

The diffusion coefficients obtained from a pile exposed to seawater are affected by the sampling locations. The FDOT Structures Design Guidelines (FDOT SDG 2007) defines the splash zone as the vertical distance from 4 feet below mean low water level (MLW) to 12 feet above mean high water level (MHW) for structural coastal crossings. This defined exposure zone is considered to be too wide for comparison purposes of diffusion coefficients. Previous researchers (Luping 2003; Sagüés et al. 2001) have shown that chloride sampling is very sensitive to the position within the splash zone where the concrete core is taken. Small differences in the core position have resulted in significant differences in the chloride profile. A common approach is to measure the location of the core sample in reference to MHW level. Moreover, additional subdivision of chloride exposure zone has been presented in previous literature (Tang and Andersen 2000; Tang, L. 2003; Cannon et al. 2006). Figure 96 shows these chloride exposure zones for a typical bridge piling surrounded by seawater. The tidal zone is the exposed area defined between the MHW and MLW marks that is intermittently subjected to chloride exposure due to changes of water tides. The submerged zone, defined as that portion of the pile below the MLW mark, is continuously exposed to salt solution. Moreover, the splash zone is above the MHW mark and is subjected to wetting and drying due to wave action. Finally, the dry zone is above the splash zone and is not directly exposed to chlorides present in seawater but may receive occasional airborne chlorides. There is no general agreement in current literature that defines where the splash zone ends and the dry zone begins. The results presented in this section are based on samples obtained in the tidal zone of exposure.

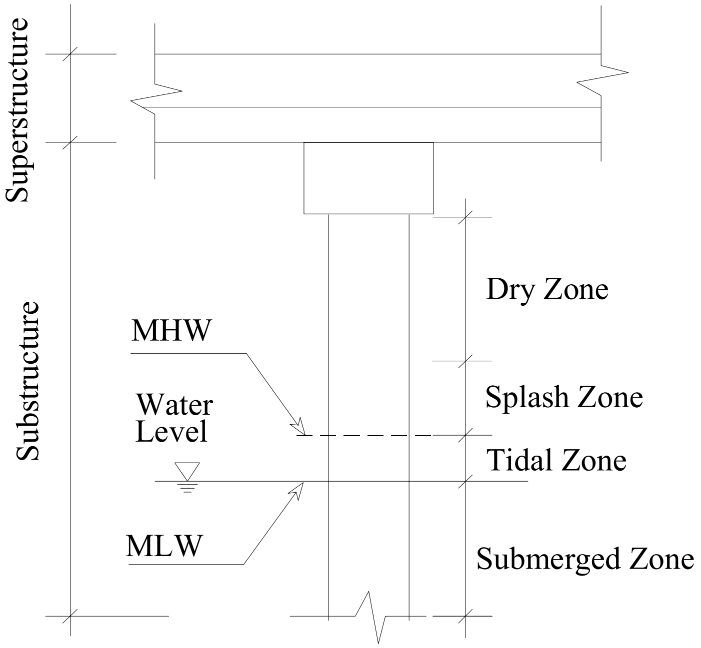


Figure 96. Chloride Exposure Zones of a Typical Bridge Structure.

Diffusion is believed to be the predominant chloride ingress mechanism for samples obtained from the submerged zone because the concrete is continuously exposed to salt solution similar to the laboratory test Bulk Diffusion. The chloride concentration in the seawater surrounding the pile is usually relatively constant. The chlorides ions will naturally migrate from the high concentration on the outside (high energy) to the low concentration (low energy) in the inside with a constant moisture present along the path of migration. When the pile is not continuously submerged, other chloride ingress mechanisms tend to control the chloride penetration.

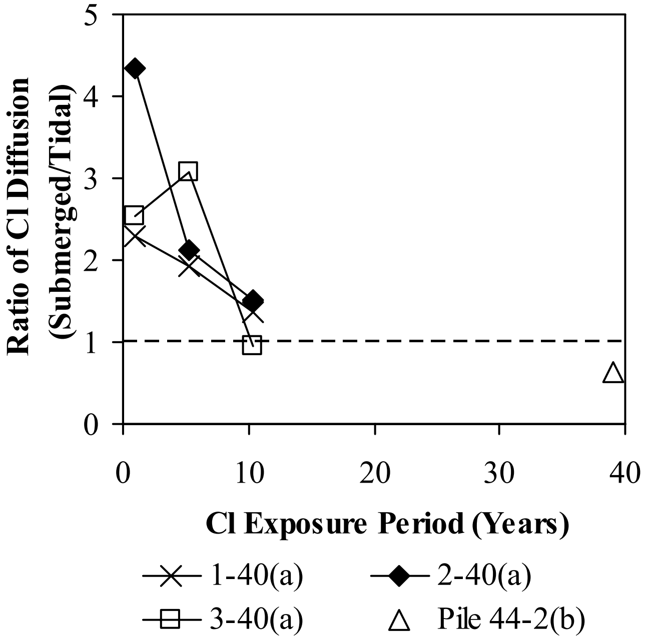
Previous research (Tang and Andersen 2000; Tang 2003) that compared samples exposed to the different zones over a 5 year period showed that the diffusion coefficients were highest in the submerged zone followed by tidal, splash and dry zone. Tang (2003) showed, however, that when the exposure period was 10 years, the chloride ingress in the tidal zone significantly increased during the period from year 5 to year 10. Table 43 summarizes the results of this previous research. The table also includes diffusion coefficients calculated from chloride sampling on 39-year old piles extracted during a bridge demolition (Cannon et al., 2006). Diffusion analyses for each of these cored samples are summarized in APPENDIX E. The diffusion coefficients from the 39-year old piles appear to confirm the trend implied by Tang's work.

Table 43 also includes the ratio of the diffusion coefficient for the submerged zone to that of the tidal zone. These ratios are plotted in Figure 97 and show a decreasing trend over the life of the structure. Indeed the data from the 39-year old piles constructed with a completely different mixture appears to confirm the decreasing trend that Tang's work implies.

Table 43. Time Dependent Changes in Diffusion Coefficients from Submerged and Tidal Zones.

Mixture	Chloride Exposure Zone	Diffusion Coefficient ($x10^{-12}$) (m^2/sec)			
		Exposed for 0.6-1.3 years	Exposed for 5.1-5.4 years	Exposed for 10.1-10.5 years	Exposed for ~39 years
1-40[(a)(c)]	**Submerged**	4.55	2.51	1.95	-
	Tidal	1.98	1.31	1.43	-
	Ratio (Sub./Tidal)	**2.30**	**1.92**	**1.36**	-
2-40 [(a) (c)]	**Submerged**	2.35	1.93	1.67	-
	Tidal	0.54	0.91	1.10	-
	Ratio (Sub./Tidal)	**4.35**	**2.12**	**1.52**	-
3-40[(a) (d)]	**Submerged**	3.78	1.26	1.25	-
	Tidal	1.49	0.41	1.33	-
	Ratio (Sub./Tidal)	**2.54**	**3.07**	**0.94**	-
Pile 44-2[(b) (c)]	**Submerged**	-	-	-	11.48
	Tidal	-	-	-	18.27
	Ratio (Sub./Tidal)	-	-	-	**0.63**

(a) Tang, L. 2003.
(b) Cannon et al. 2006.
(c) Plain cement concrete mixture. No additional cementitious materials were added.
(d) Concrete mixture containing silica fume.



(a) Tang, L. 2003.
(b) Cannon et al. 2006.

Figure 97. Time Dependent Changes in Diffusion Coefficients from Submerged and Tidal Zones

The trend illustrated in Figure 97 might be used to relate the results of bulk diffusion test to those of the field cores obtained from the bridges in service. If it is assumed that the environmental conditions of the bulk diffusion test are similar to those of the completely submerged pile in service, then the diffusion coefficients can be compared to give a reasonable correlation between laboratory tests and field conditions. From this viewpoint, the plot in Figure 97 indicates that the bulk diffusion test will likely give the highest diffusion coefficient for concretes less than about ten years old. As the concrete ages, however, the tidal zone diffusion coefficient appears to exceed that of the submerged zone signifying that the bulk diffusion test might not give the most conservative results.

This connection can be tested by comparing the results of the one-year bulk diffusion testing to the diffusion coefficients of the piles from which the samples were collected for this research, as long as the mixture proportions and constituents are comparable. The diffusion coefficients from mixture design CPR8 (Table 8) are compared to diffusion coefficients from extracted cores that were taken from piles that used a similar mixture design (including the addition of silica fume). The comparison is based on the cores taken at the tidal zone. Additionally, available chloride profiles from FDOT research currently in progress (Paredes 2007) were included in this analysis. Table 44 shows the summary of the calculated laboratory diffusion coefficients with the statistical parameters average and standard deviation. Detailed data on these calculations are presented in APPENDIX E.

Figure 98 shows the diffusion coefficients of the selected laboratory and field samples plotted on a logarithmic scale. The field samples used in the plot were selected because they were extracted from tidal zone. There is nearly an order of magnitude difference between the diffusion coefficients from the bulk diffusion tests and those from the field-cored samples. This variation can be attributed to the several factors affecting chloride diffusion under field conditions as the sampling location and the concrete ageing.

Assuming that the ratio of the submerged to tidal diffusion coefficients is controlled primarily by environment, then the ratios from Table 43 can be used to "convert" the tidal diffusion coefficient to a submerged diffusion coefficient. Although this assumption is probably not strictly correct since variation in concrete permeability will likely affect the ratio as well, it makes a convenient method by which the laboratory results can be related to field results. Because the piles sampled for this research were approximately ten years in service, the highest calculated ratio of 1.52 for a comparable age of exposure of 10 years will give the most conservative result. Applying this ratio to the field results ostensibly converts those diffusion coefficients to a submerged condition as is shown in Figure 98. Comparing these diffusion coefficients to the laboratory diffusion coefficients indicates that the 1-year bulk diffusion coefficients are higher than the field values for a ten year period.

It is not clear why 1-year laboratory values are higher than the ten-year field values. This analysis considered only the diffusion coefficients and not the chloride content at the level of the steel. The diffusion coefficients are derived from fitting a curve to the chloride profile data. It perhaps gives a better indication of the shape of the curve rather than a direct indication of the chloride content at a certain depth. Further data are needed to better characterize this time dependency. One suggestion is to obtain shorter and longer exposure periods in the laboratory samples to establish time variations of the diffusion for the laboratory samples. This trend can then be used to establish correlation with the longer-term results obtained from the field on comparable mixtures. Nevertheless, it appears that the 1-year bulk diffusion results overestimate the diffusion coefficients from ten-year old concrete in the field.

Table 44. Laboratory Bulk Diffusion Coefficients for Comparable Mixtures with an Expected Low Chloride Permeability Design.

Mixture[(a)]	**Sample ID**	**364-Day Bulk Diffusion Coefficient ($x10^{-12}$) (m^2/sec)**		
		Results	**Average**	**Standard Deviation**
CPR8	**A**	2.351	2.220	0.744
	B	2.729		
	C	3.562		
HRP3[(b)]	**A**	1.691		
	B	1.782		
HRP4[(b)]	**A**	2.071		
	B	1.355		

(a) Mixture design: w/c: 0.35, Cementitious:752 pcy, 20% Fly Ash and 8% Silica Fume.

(b) Samples obtained from FDOT research currently in progress (Paredes 2007)

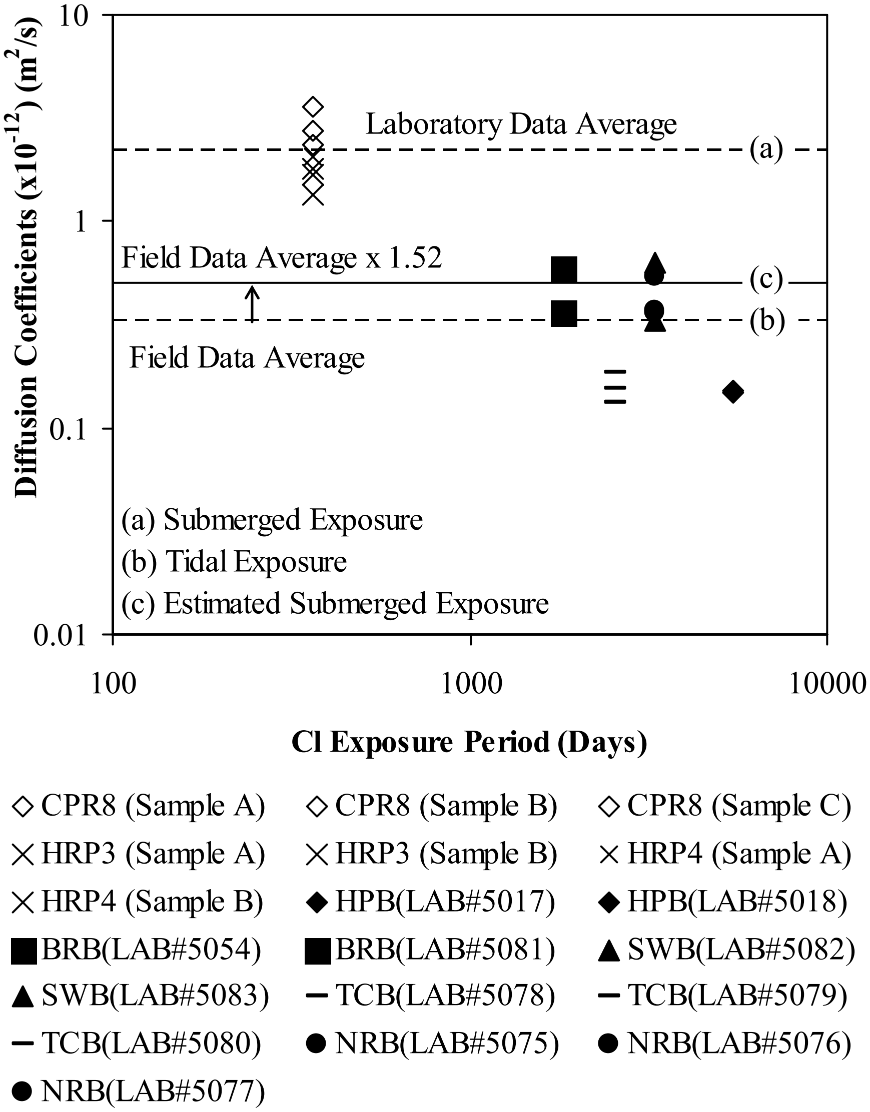


Figure 98. Time Dependent Laboratory and Field Diffusion Coefficient Trend of Change.

10 REFERENCES

AASHTO T 23 (1993). “Standard Method of Test for Making and Curing Concrete Test Specimens.” American Association of States Highway and Transportation Officials.

AASHTO T 259-80 (1993). “Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration.” American Association of States Highway and Transportation Officials.

AASHTO T 277-86 (1990). “Rapid Determination of the Chloride Permeability of Concrete.” American Association of States Highway and Transportation Officials

ASTM C 1202 (1997). “Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration.” American Society for Testing and Materials.

ASTM C 1064 (1999). “Standard Test Method for Temperature of Freshly Mixed Portland Cement Concrete.” American Society for Testing and Materials.

ASTM C 143 (2000). “Standard Test Method for Slump of Hydraulic Cement Concrete.” American Society for Testing and Materials.

ASTM C 138 (2001). “Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete.” American Society for Testing and Materials.

ASTM C 173 (2001). “Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method.” American Society for Testing and Materials.

ASTM C1152/C1152M (1990). “Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete.” American Society for Testing and Materials.

Andrade, C. and Gonzalez, J.A. (1998). “Relation Between Resistivity and Corrosion Rate of Reinforcements in Carbonated Mortar made with Several Cement Types.” Cement and Concrete Research, 18(5), 687-698.

Andrade, C. (1993). “Calculation of chloride diffusion coefficients in concrete from ionic migration measurements.” Cement and Concrete Research, 23(3), 724-742.

Andrade, C., Castellote, C., Alonso, C. and González, C. (1999). “Relation Between Colorimetric Chloride Penetration Depth and Charge Passed in Migration Tests of the Type of Standard ASTM C1202-91.” Cement and Concrete Research, 29(3), 417-421.

Baykal, M (2000). “Implementation of durability models for Portland cement concrete in to performance-based specifications.” The University of Texas at Austin College of Engineering.

Berke, N.S. and Hicks, M.C. (1992). “Estimating the Life Cycle of Reinforced Concrete Decks and Marine Piles Using Laboratory Diffusion and Corrosion Data.” Corrosion Forms and Control for Infrastructure, American Society for Testing and Materials, ASTM STP 1137, 207.

Broomfield, J., Rodriguez, J., Ortega, L.M. and Garcia, A.M (1993). “Corrosion Rate Measurement and Life Prediction for Reinforced Concrete Structures.” Proceedings of Structural Faults and Repair, 93(2), 155-164.

Broomfield, J. and Millard, S. (2002). “Measuring concrete resistivity to assess corrosion rates.” A report from The Concrete Society/Institute of Corrosion liaison committee, Current Practice Sheet (128), 37-39.

Brown, R.P and Kessler, R.J. (1978). “An Accelerated Laboratory Method for Corrosion Testing of Reinforced Concrete Using Impressed Current.” Final Report No. HPR-PR-1(14), Part II, Florida Department of Transportation..

Browne, R. (1980). “Mechanisms of Corrosion of Steel in Concrete in Relation to Design, Inspection, and Repair of Offshore and Coastal Structures.” ACI Special Publications, 65, 169-204.

Cannon, E., Lewinger, C., Abi, C. and Hamilton, H. R. (2006). “St. George Island Bridge Pile Testing”. Final Report No. BD545, Florida Department of Transportation.

Chini, A.R, Muszynski, L.C. and Hicks, J. (2003). “Determination of Acceptance Permeability Characteristics for Performance-Related Specifications for Portland Cement Concrete.” Final Report No. BC 354-41, Florida Department of Transportation.

Dhir, R.K., and Byars, E.A. (1993). “PFA concrete: Chloride diffusion rates.” Magazine of Concrete Research, 45(162), 1-9.

Feldman, R.F., Chan, G.W., Brousseau, R.J. and Tumidajski, P.J. (1994). “Investigation of the Rapid Chloride Permeability Test.” ACI Materials Journal, 91(3), 246-255.

FDOT 346 (2004). “Florida Department of Transportation Standard Specification for Road and Bridge Construction.” Florida Department of Transportation (FDOT). 346-3.1(d).

FM 5-516 (2005). “Florida Method of Test For Determining Low-Levels of Chloride in Concrete and Raw Materials.” Florida Department of Transportation (FDOT).

FM 5-522 (2000). “Florida Method of Test for An Accelerated Laboratory Method for Corrosion Testing of Reinforced Concrete Using Impressed Current.” Florida Department of Transportation (FDOT).

FM 5-578 (2004). “Florida Method of Test for Concrete Resistivity as an Electrical Indicator of its Permeability.” Florida Department of Transportation (FDOT).

FDOT SDG 2007. "Structures Design Guidelines." Florida Department of Transportation (FDOT).

Glass, G.K., and Buenfeld, N.R. (1995). "Chloride threshold levels for corrosion induced deterioration of steel in concrete." International RILEM Workshop.

Gowers, K.R. and Millard, S.G. (1999). "Measurement of Concrete Resistivity for Assessment of Corrosion Severity of Steel Using Wenner Technique." ACI Materials Journal, 96(5), 536-541.

Hartt, W.H. and Brown, R.P (1979). "Laboratory Method for Corrosion Testing of Reinforced Concrete Using Impressed Current." NACE Meeting, Atlanta, Georgia.

Hooton, R.D. (1997). "Discussion of the rapid chloride permeability test and its correlation to the 90-day chloride ponding test." PCI Journal, 42(3), 65-66.

Hooton, R.D.,Thomas, M.D.A. and Stanish, K. (2001). "Prediction of Chloride Penetration in Concrete." Final Report No. FHWA/RD-00/142, Federal Highway Administration.

Hughes, B.P., Soleit, A.K.O. and Brierly, R.W. (1985). "New Technique for Determining the Electrical Resistivity of Concrete." Magazine of Concrete Research, 37(133), 243-248.

Langford, P. and Broomfield, J. (1987). "Monitoring the Corrosion of Reinforcing Steel." Construction Repair, 1(2), 32-36.

Larsen, T.J., McDaniel, W.H., Brown, R.P. and Sosa, J.L. (1975). "Corrosion Inhibiting Properties of Portland-Pozzolan Cement Concretes." Status Report, Florida Department of Transportation. Presented TRB Meeting, Washington, D.C.

Li, Z., Peng, J., and Ma, B. (1999). "Investigation of chloride diffusion for high-performance concrete containing fly ash, microsilica, and chemical admixtures." ACI Materials Journal, 96(3), 391-396.

McGrath, P.F. and Hooton, R.D. (1999). "Re-evaluation of the AASHTO T259 90-day salt ponding test." Cement and Concrete Research, 29(8), 1239-1248.

Meck, E. and Sirivivatnanon, V. (2003). "Field Indicator of Chloride Penetration Depth." Cement and Concrete Research, 33(8), 1113-1117.

Mindess, S., Young, J.F and Darwin, D. (2002). "Concrete." *Second Edition, Prentice-Hall.*

Monfore, G.E. (1968). "The Electrical Resistivity of Concrete." Journal of the PCA Research and Development Laboratories, 10(2), 35-48.

Morris, W., Moreno, E.I. and Sagües, A.A. (1996). "Practical evaluation of resistivity of concrete in test cylinders using a Wenner array probe." Cement and Concrete Research, 26(12), 1779-1787.

Nokken, M., Boddy, A., Hooton, R.D. and Thomas, M.D.A. (2006). “Time Dependent Diffusion in Concrete—Three Laboratory Studies.” Cement and Concrete Research, 36(1), 200-207.

NT BUILD 443 (1995). “Concrete, hardened: Accelerated chloride penetration.” Nordtest method.

NT BUILD 492 (1999). “Concrete, mortar and cement-based repair materials: Chloride Migration Coefficient from Non-Steady-Stade Migration Experiments.” Nordtest Method.

Otsuki, N., Nagataki, S. and Nakashita, K. (1992). “Evaluation of AgNO3 Solution Spray Method for Measurement of Chloride Penetration Into Hardened Cementitious Matrix Materials.” ACI Materials Journal. 89(6) 587–592.

Ozyildirim, C., and Halstead, W.J. (1988). “Use of Admixtures to Attain Low Permeability Concretes” Final Report No. FHWA/VA-88-R11.

Page, C.L., Short, N.R., and El Tarras, A. (1981). “Diffusion of chloride ions in hardened cement pastes.” Cement and Concrete Research, 11(3), 395-406.

Paredes, M. (2007). “High Reactive Pozzolans Project (HRP)”. Project in Progress. Florida Department of Transportation.

Pfeifer, D.W., McDonald, D.B. and Krauss, P.D. (1994). “The rapid chloride permeability test and its correlation to the 90-day chloride ponding test.” PCI Journal, 41(4), 82–95.

Sagüés, A.A., Kranc, S.C., Presuel-Moreno, F., Rey, D., Torres-Acosta, A. and Yao, L. (2001). “Corrosion Forecasting for 75-Year Durability Design of Reinforced Concrete.” Final Report No. BA 502, Florida Department of Transportation.

Scanlon, J.M. and Sherman, M.R. (1996). “Fly ash concrete: An evaluation of chloride penetration testing methods.” Concrete International, 18(6), 57-62.

Shi, C., Stegemenn, J.A. and Caldwell, R. (1998). “Effect of Supplementary Cementing Materials on the Specific Conductivity of Pore Solution and Its Implications on the Rapid Chloride Permeability Test (AASHTO T277 and ASTM C1202) Results.” ACI Materials Journal, 95(4), 389-394.

Shi, C. (2003). “Another look at the Rapid Chloride Permeability Test (ASTM C1202 or AASHTO T277).”

Sirivivatnanon, V. and Khatri, R. (1998). “Chloride penetration resistance of concrete. Getting a Lifetime out of Concrete Structures.” Concrete Institute of Australia Conference. Brisbane, Australia.

Snyder, K.A., Ferraris, C., Martys, N.S. and Garboczi, E.J. (2000). “Using Impedance Spectroscopy to Assess the Viability of the Rapid Chloride Test for determining Concrete Conductivity.” Journal of Research of the National Institute of Standars and Technology, 105(4), 497-509.

Spellman, D.L., and Stratfull R.F. (1973). “Concrete Variables and Corrosion Testing.” Highway Research Record 423, 27-45.

Stanish, K. and Thomas, M. (2003). “The use of bulk diffusion tests to establish time-dependent concrete chloride diffusion coefficients.” Cement and Concrete Research, 33(1), 55-62.

Streicher, P.E and Alexander, M.G. (1994). “A Critical Evaluation of Chloride Diffusion Test Methods for Concrete.” Third CANMET/ACI International Conference on Durability of Concrete, Supplementary Papers, 517-530.

Streicher, P.E and Alexander, M.G. (1995). “A Chloride Conduction Test for Concrete.” Cement and Concrete Research, 25(6), 1284-1294.

Tang, L. and Nilsson, L. (1992). “Rapid Determination of the Chloride Diffusivity in Concrete by Applying an Electrical Field.” ACI Materials Journal, 89(1), 49-53.

Tang, L. and Andersen, A. (2000). “Chloride ingress data from five years field exposure in a Swedish marine environment”. Proceedings of the 2nd International RILEM Workshop on Testing and Modelling the Chloride Ingress into Concrete, Paris, 11-12, pp. 105-119.

Tang, L. (2003). “Chloride Ingress in Concrete Exposed to Marine Environment–Field data up to 10 years exposure”. SP Swedish National Testing and Research Institute Building Technology and Mechanics. SP REPORT 2003:16.

Thomas, M.D.A., Pantazopoulou, S.J. and Martín-Pérez, B. (1995). “Service Life Modelling of Reinforced Concrete Structures Exposed to Chlorides: A Literature Review.” Department of Civil Engineering, University of Toronto, 45.

Tuutti, K. (1982). “Corrosion of steel in concrete.” Swedish Cement and Concrete Research Institute, 469.

Whiting, D. (1981). “Rapid determination of the chloride ion permeability of concrete.” Federal Highway Administration, Final Report No. FHWA/RD-81/119.

Whiting, D. (1988). “Permeability of Selected Concretes.” Permeability of Concrete, SP-108, American Concrete Institute. 195-222.

Whiting, D., and Dziedzic, W. (1989). “Resistance to Chloride Infiltration of Superplasticized Concrete as Compared With Currently Used Concrete Overlay Systems.” Final Report No. FHWA/OH-89/009.

Whiting, D. and Mohamad, N. (2003). “Electrical Resistivity of Concrete-A Literature Review.” Portland Cement Association, R&D Serial No. 2457.

Wee, T.H., Suryavanshi, A.K. and Tin, S.S. (2000). “Evaluation of Rapid Chloride Permeability Test (RCPT) Results for Concrete Containing Mineral Admixtures.” ACI Materials Journal, 97(2), 221-232.

Yang, C.C., Cho, S.W. and Huang, R. (2002). "The relationship between charge passed and the chloride-ion concentration in concrete using steady-state chloride migration test." Cement and Concrete Research, 32(2), 217-22.

APPENDIX A

CONCRETE COMPRESSIVE STRENGTH DATA RESULTS.

MIX CPR1

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	5442	5502	5732	5559
28	5710	5745	5690	5715
56	6214	5992	6321	6176
91	6400	6208	6510	6373
182	6638	6247	6217	6367
364	6594	6145	6314	6351

MIX CPR2

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	7952	7914	8104	7990
28	8462	7857	8030	8116
56	8814	8576	7703	8364
91	8681	8608	8194	8494
182	8371	8768	8738	8626
364	8842	8817	8842	8834

MIX CPR3

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	5869	5866	5782	5839
28	6352	6284	6219	6285
56	6293	6431	6442	6389
91	6300	6411	6390	6367
182	7185	6990	7023	7066
364	6768	7295	6779	6947

MIX CPR4

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	8382	8434	8531	8449
28	9122	9058	8797	8992
56	9261	9198	9173	9211
91	9475	9620	9499	9531
182	9406	9416	9073	9298
364	9077	9416	9908	9467

MIX CPR5

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	6797	6686	7079	6854
28	7441	7354	7023	7273
56	8376	8393	7942	8237
91	8482	8390	8471	8448
182	9016	8601	8533	8717
364	9212	9323	9089	9208

MIX CPR6

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	5784	6053	5722	5853
28	6163	6386	6327	6292
56	6682	7004	6889	6858
91	7505	7251	7295	7350
182	7745	7444	7405	7531
364	7670	8086	7600	7785

MIX CPR7 ▨ Sample not included in Average

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	7709	7850	7026	7528
28	8082	8343	8861	8429
56	8995	8896	8158	8683
91	8161	9410	8924	8832
182	9483	8424	8891	8933
364	8951	9111	▨ 7379	9031

MIX CPR8

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	6533	6536	6342	6470
28	7106	6969	7153	7076
56	6936	7499	7515	7317
91	7072	5224	7475	6590
182	7535	7969	8004	7836
364	8007	7198	7769	7658

MIX CPR9

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	8493	8957	8795	8748
28	8681	8541	8443	8555
56	8792	9418	8996	9069
91	8352	8117	8225	8231
182	9239	9028	9335	9201
364	9520	9018	9962	9500

MIX CPR10

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	7768	7727	8195	7897
28	8098	8598	8169	8288
56	8582	8939	8593	8705
91	8964	8859	9078	8967
182	9573	9277	9343	9398
364	9050	9489	9270	9270

MIX CPR11

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
17	7251	6858	8007	7372
28	7647	8109	8101	7952
56	8021	7883	8460	8121
91	7940	8016	8236	8064
182	8629	8035	8323	8329
364	8547	8752	8649	8649

MIX CPR13

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	5710	6065	5927	5901
28	6425	6432	6705	6521
56	7550	7398	6725	7224
91	7625	7392	6862	7293
182	7940	7314	7421	7558
364	8258	7996	7879	8044

MIX CPR16

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	5926	6448	5792	6055
28	6388	5629	6303	6107
56	6942	7645	6761	7116
91	7658	6427	7687	7257
182	7674	8234	7854	7921
364	7533	7904	8683	8040

MIX CPR18

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	5835	6126	6792	6251
28	6709	6934	6962	6868
56	7163	6954	8076	7398
91	8112	8196	8211	8173
182	9137	8634	8747	8839
364	8644	9366	9370	9127

MIX CPR21

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	5298	5697	5601	5532
28	5940	6252	6112	6101
56	7138	7707	7209	7351
91	7396	8691	7512	7866
182	8910	8333	8294	8512
364	8689	9270	8691	8883

MIX CPR12

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	5257	5893	5264	5471
28	5824	5035	5633	5497
56	6573	6375	5373	6107
91	6323	6598	5689	6203
182	6351	6072	5871	6098
364	6562	5320	7732	6538

MIX CPR15

Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	4036	3275	3904	3738
28	5069	4633	3768	4490
56	5826	4982	4961	5256
91	6208	5309	5871	5796
182	6070	6151	6709	6310
364	6094	6614	6673	6460

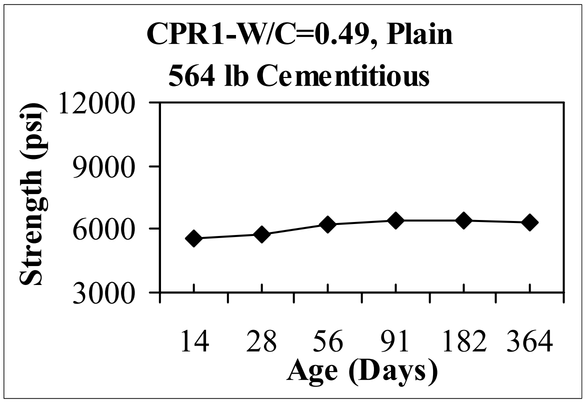
MIX CPR17

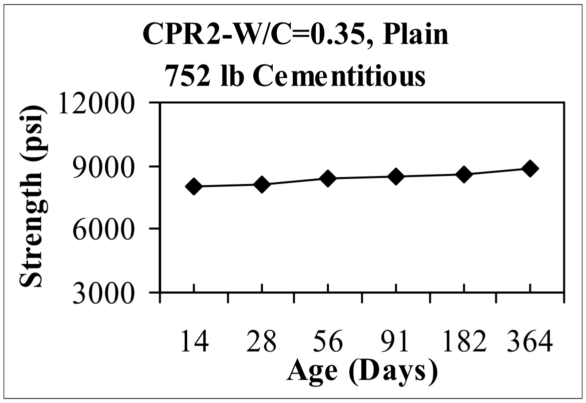
Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	6241	5525	7198	6321
28	7052	7056	7612	7240
56	7926	7986	7979	7964
91	8024	8284	8345	8218
182	9808	9678	8409	9298
364	10314	10308	10425	10349

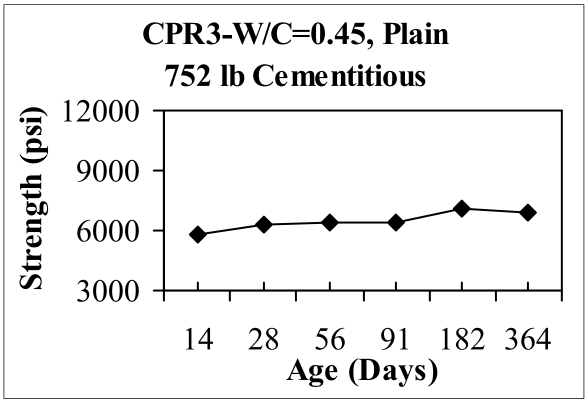
MIX CPR20

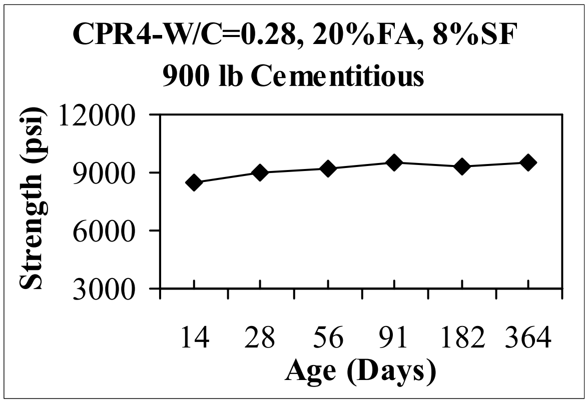
Testing Age	COMPRESSIVE STRENGTH (psi)			
(Days)	A	B	C	AVG.
14	8889	8976	8987	8951
28	10125	9521	9510	9719
56	10116	11309	10036	10487
91	11368	10708	11696	11257
182	12044	11159	11383	11529
364	12337	11634	11221	11731

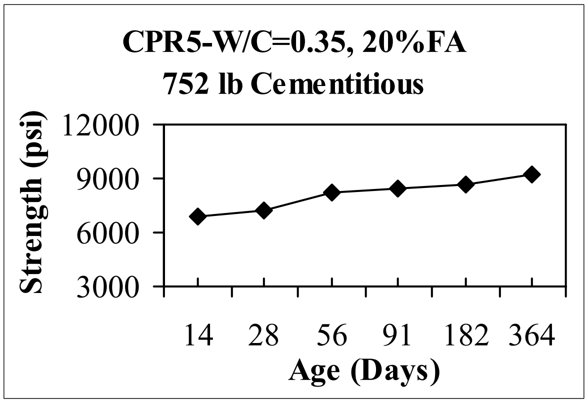
Concrete Compression Strength Graphs.

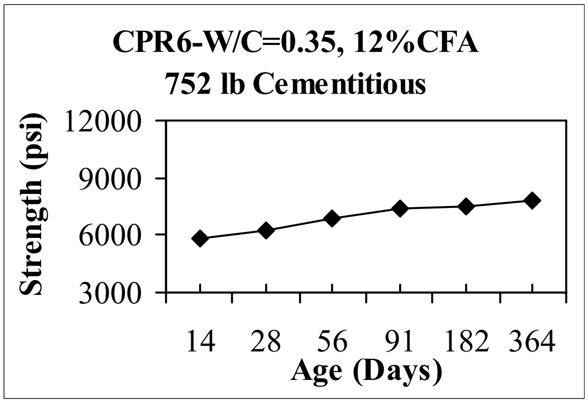

CPR1-W/C=0.49, Plain
564 lb Cementitious

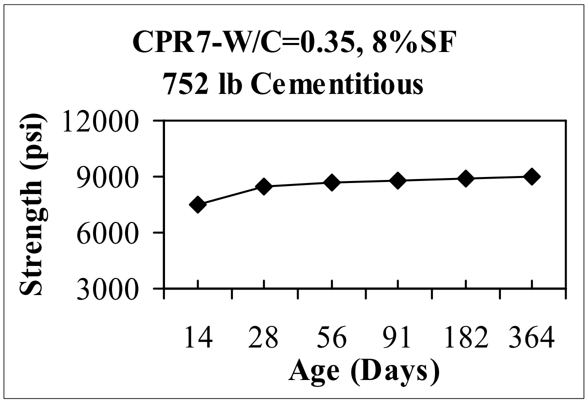

CPR2-W/C=0.35, Plain
752 lb Cementitious

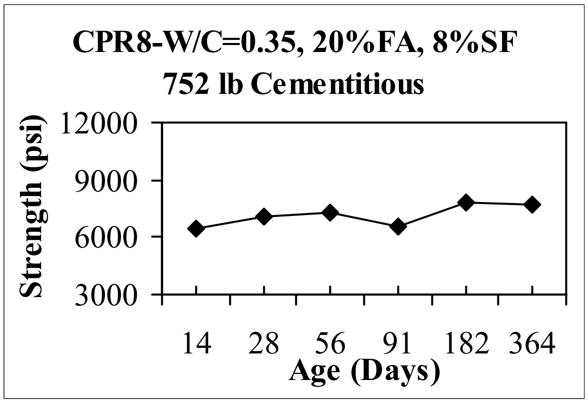

CPR3-W/C=0.45, Plain
752 lb Cementitious


CPR4-W/C=0.28, 20%FA, 8%SF
900 lb Cementitious

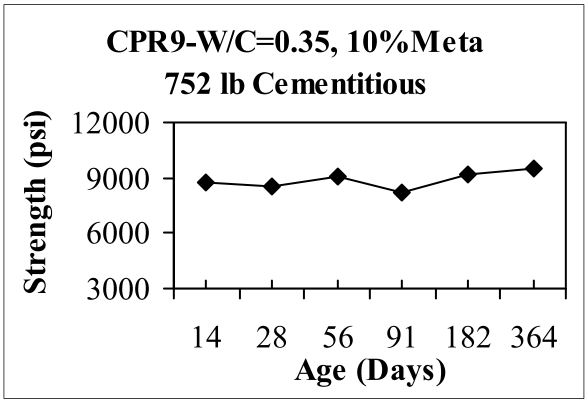

CPR5-W/C=0.35, 20%FA
752 lb Cementitious

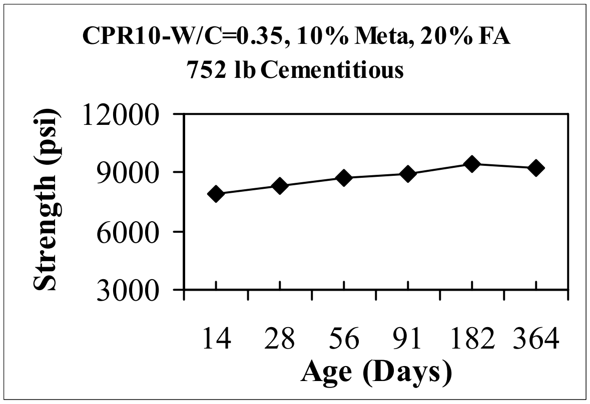

CPR6-W/C=0.35, 12%CFA
752 lb Cementitious

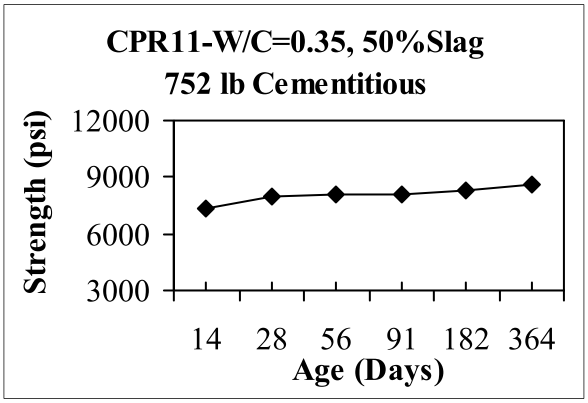

CPR7-W/C=0.35, 8%SF
752 lb Cementitious

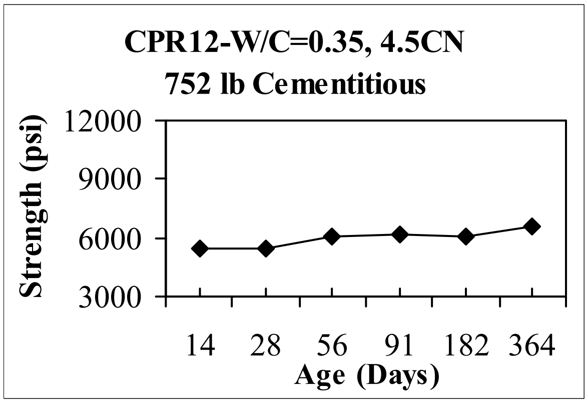

CPR8-W/C=0.35, 20%FA, 8%SF
752 lb Cementitious

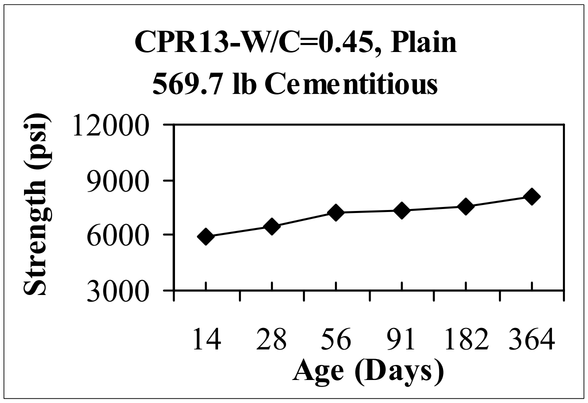
Concrete Compression Strength Graphs.

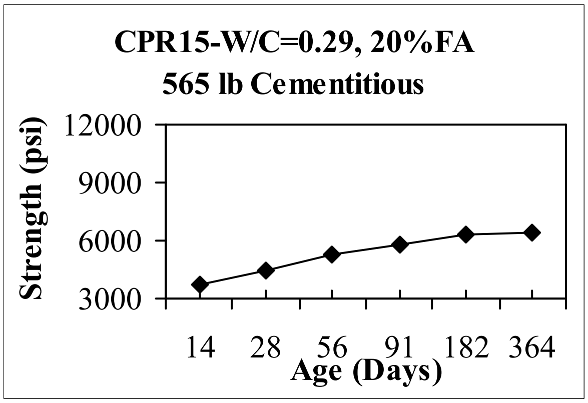


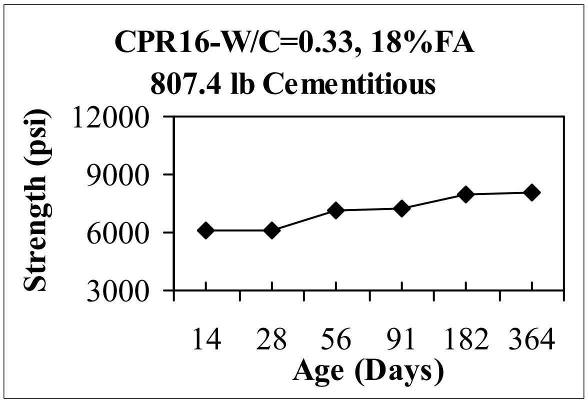


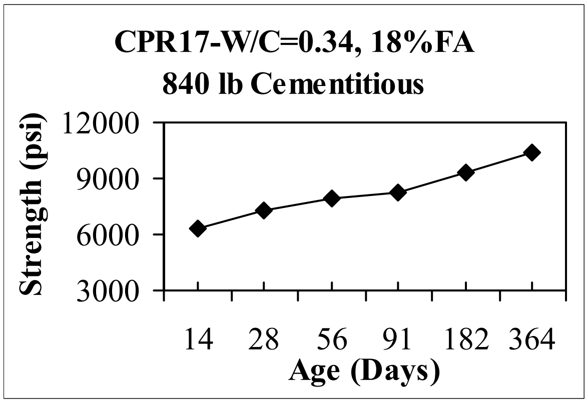




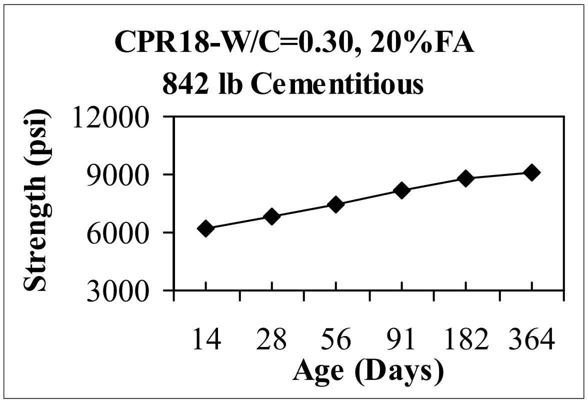


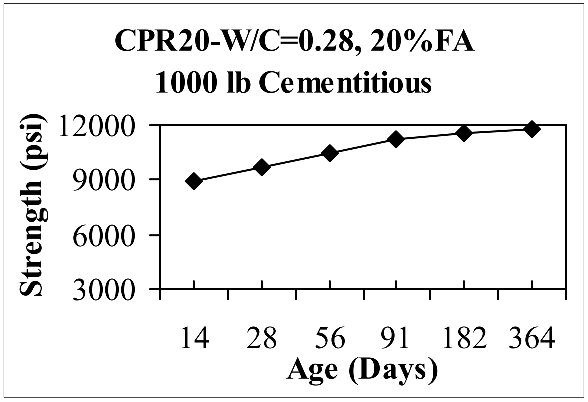


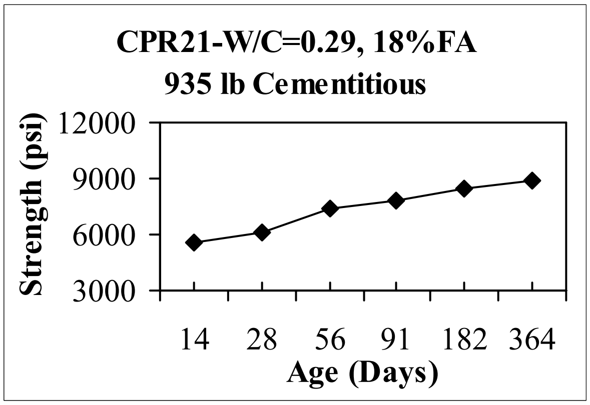




Concrete Compression Strength Graphs.







APPENDIX B

LONG-TERM CHLORIDE PENETRATION PROCEDURES (BULK DIFFUSION AND T259 PONDING TEST) TEST DATA AND ANALYSIS RESULTS.

Appendix Table of Contents

Diffusion 1. Fick's Diffusion Laws.

Fick's First Law describes the flow of an impurity in a substance, showing that the rate of diffusion of the material across a given plane is proportional to the concentration gradient across that plane. It states for chloride diffusion into concrete or for any diffusion process considered in one-dimensional situation that:

$$J = -D_{eff} \frac{dC}{dx}$$

where J is the rate of diffusion of the chloride ions, D_{eff} is the effective diffusion coefficient, C is the concentration of chloride ions, and x is a position variable. The minus sign means that mass is flowing in the direction of decreasing concentration. The effective diffusion coefficient considered the effect of the chloride ions movement through a heterogeneous material like the concrete. Hence, the rate of diffusion calculated includes the effect of the concrete porous matrix that contains both solid and liquid components. The equation can be used only when no changes in concentration in time are present.

Fick's Second Law is a derivation of the first law to represent the changes of concentration gradient with time. It states that for the effective diffusion coefficient (D_{eff}) the rate of change in concentration with time (t) is proportional to the rate at which the concentration gradient changes with distance in a given direction:

$$\frac{\partial C}{\partial t} = D_{eff} \frac{\partial^2 C}{\partial x^2}$$

If the following boundary conditions are assumed: surface concentration is constant ($C_{(x=0,\, t>0)} = C_0$), initial concentration in the concrete is cero ($C_{(x>0,\, t=0)} = 0$) and concentration at an infinite point far enough from the surface is cero $C_{(x=\infty,\, t>0)} = 0$). The equation can then be reduced to:

$$\frac{C(x,t)}{C_0} = 1 - erf\left(\frac{x}{\sqrt{4 \times D_{eff} \times t}}\right)$$

where erf is the error function. Tables with values of the error function are given in standard mathematical reference books.

Diffusion 2. Initial Chloride Background Level of Concrete Mixtures.

Mixture Name	Concrete Unit Weight (pcf)	Initial Chloride Samples (lb/yd^3)				Average Initial Chlorides (%Concrete)
		A	B	C	Average	
CPR1	140.62	0.112	0.149	0.137	0.133	0.004
CPR2	144.62	0.097	0.053	0.087	0.079	0.002
CPR3	140.40	0.093	0.136	0.145	0.125	0.003
CPR4	142.32	0.192	0.130	0.130	0.151	0.004
CPR5	144.32	0.181	0.112	0.126	0.140	0.004
CPR6	140.52	0.097	0.114	0.110	0.107	0.003
CPR7	143.72	0.284	0.204	0.212	0.233	0.006
CPR8	139.72	0.077	0.111	0.101	0.096	0.003
CPR9	145.22	0.070	0.076	0.080	0.075	0.002
CPR10	144.02	0.087	0.070	0.066	0.074	0.002
CPR11	142.82	0.146	0.209	0.200	0.185	0.005
CPR12	140.49	0.147	0.139	0.136	0.141	0.004
CPR13	140.49	0.181	0.174	0.178	0.178	0.005
CPR15	148.64	0.467	0.546	0.533	0.515	0.013
CPR16	145.01	0.124	0.130	0.125	0.126	0.003
CPR17	143.08	0.187	0.212	0.139	0.179	0.005
CPR18	148.77	0.221	0.274	0.281	0.259	0.006
CPR20	142.16	0.146	0.100	0.112	0.119	0.003
CPR21	147.39	0.323	0.286	0.338	0.316	0.008

Diffusion 3. 364-Day Bulk Diffusion Chloride Profile Testing Results (CPR1 to CPR6 Mixtures).

MIX CPR1
Unit W. 140.62 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	34.55	38.94	36.23	36.57	0.963
9.53	26.32	29.11	23.79	26.41	0.695
15.88	23.14	21.45	21.01	21.87	0.576
22.23	17.01	18.18	18.61	17.93	0.472
28.58	14.09	14.49	13.57	14.05	0.370
34.93	12.54	11.26	10.13	11.31	0.298
41.28	9.39	9.12	8.52	9.01	0.237
47.63	6.88	6.77	6.29	6.65	0.175
53.98	5.74	4.51	4.17	4.81	0.127
60.33	4.96	3.35	2.78	3.70	0.097
66.68	4.42	2.21	1.69	2.77	0.073
73.03	3.86	1.35	0.99	2.07	0.054

MIX CPR2
Unit W. 144.62 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	39.66	42.40	39.41	40.49	1.037
9.53	24.83	27.06	27.00	26.30	0.673
15.88	16.31	17.00	15.94	16.42	0.421
22.23	8.23	10.62	10.42	9.76	0.250
28.58	2.46	3.73	5.09	3.76	0.096
34.93	0.60	1.15	1.58	1.11	0.028
41.28	0.20	0.45	0.41	0.35	0.009
47.63	0.21	0.44	0.26	0.30	0.008
53.98	-	-	-	-	-
60.33	-	-	-	-	-
66.68	-	-	-	-	-
73.03	-	-	-	-	-

MIX CPR3
Unit W. 140.40 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	46.11	48.04	46.62	46.92	1.238
9.53	30.35	35.39	33.34	33.03	0.871
15.88	23.42	22.52	22.26	22.73	0.600
22.23	18.90	17.60	18.46	18.32	0.483
28.58	12.99	14.95	13.15	13.70	0.361
34.93	9.48	9.74	8.80	9.34	0.246
41.28	6.72	5.86	5.61	6.07	0.160
47.63	4.33	3.50	3.01	3.61	0.095
53.98	2.19	2.10	1.21	1.83	0.048
60.33	1.01	1.23	0.51	0.91	0.024
66.68	-	-	-	-	-
73.03	-	-	-	-	-

MIX CPR4
Unit W. 142.32 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	38.99	42.39	35.51	38.96	1.014
9.53	17.07	16.20	14.25	15.84	0.412
15.88	3.55	3.70	3.36	3.54	0.092
22.23	0.86	0.97	1.20	1.01	0.026
28.58	0.52	0.48	0.55	0.52	0.013
34.93	0.34	0.37	0.35	0.35	0.009
41.28	0.37	0.38	0.31	0.35	0.009
47.63	0.30	0.31	0.29	0.30	0.008
53.98	-	-	-	-	-
60.33	-	-	-	-	-
66.68	-	-	-	-	-
73.03	-	-	-	-	-

MIX CPR5
Unit W. 144.32 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	38.78	40.83	41.40	40.34	1.035
9.53	27.84	29.11	24.52	27.16	0.697
15.88	14.00	18.22	15.87	16.03	0.411
22.23	7.22	9.06	10.60	8.96	0.230
28.58	3.96	5.21	7.27	5.48	0.141
34.93	2.64	3.29	5.61	3.85	0.099
41.28	2.48	3.22	4.14	3.28	0.084
47.63	2.13	2.89	4.20	3.07	0.079
53.98	2.62	3.27	4.38	3.42	0.088
60.33	2.42	2.95	4.13	3.17	0.081
66.68	-	-	-	-	-
73.03	-	-	-	-	-

MIX CPR6
Unit W. 140.52 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	46.15	50.75	52.24	49.71	1.310
9.53	33.32	35.79	33.17	34.09	0.899
15.88	21.57	22.17	20.23	21.32	0.562
22.23	12.99	11.79	12.54	12.44	0.328
28.58	5.99	4.71	5.55	5.42	0.143
34.93	2.06	1.48	1.62	1.72	0.045
41.28	0.61	0.55	0.51	0.56	0.015
47.63	0.42	0.34	0.35	0.37	0.010
53.98	-	-	-	-	-
60.33	-	-	-	-	-
66.68	-	-	-	-	-
73.03	-	-	-	-	-

Diffusion 4. 364-Day Bulk Diffusion Chloride Profile Testing Results (CPR7 to CPR12 Mixtures).

MIX CPR7
Unit W. 143.72 (pcf)

Depth (mm)	NaCl (lb/yd^3) A	B	C	AVG	AVG. NaCl (%Conc)
3.18	43.90	43.25	45.92	44.35	1.143
9.53	22.24	25.09	20.44	22.59	0.582
15.88	11.42	9.79	8.10	9.77	0.252
22.23	4.15	2.41	2.65	3.07	0.079
28.58	1.08	1.00	0.54	0.87	0.022
34.93	0.44	0.52	0.32	0.43	0.011
41.28	0.30	0.42	0.28	0.33	0.009
47.63	0.32	0.35	0.26	0.31	0.008
53.98	-	-	-	-	-
60.33	-	-	-	-	-
66.68	-	-	-	-	-
73.03	-	-	-	-	-

MIX CPR8
Unit W. 139.72 (pcf)

Depth (mm)	NaCl (lb/yd^3) A	B	C	AVG	AVG. NaCl (%Conc)
3.18	43.41	52.65	47.41	47.83	1.268
9.53	26.44	33.02	31.48	30.31	0.804
15.88	10.19	15.29	17.03	14.17	0.376
22.23	2.07	4.14	7.74	4.65	0.123
28.58	0.44	0.78	2.20	1.14	0.030
34.93	0.29	0.28	0.49	0.35	0.009
41.28	0.26	0.33	0.32	0.30	0.008
47.63	0.23	0.25	0.25	0.24	0.006
53.98	-	-	-	-	-
60.33	-	-	-	-	-
66.68	-	-	-	-	-
73.03	-	-	-	-	-

MIX CPR9
Unit W. 145.22 (pcf)

Depth (mm)	NaCl (lb/yd^3) A	B	C	AVG	AVG. NaCl (%Conc)
3.18	48.11	45.02	56.63	49.92	1.273
9.53	14.64	17.55	22.06	18.08	0.461
15.88	1.92	4.01	5.60	3.84	0.098
22.23	0.31	0.76	1.26	0.77	0.020
28.58	0.17	0.30	0.32	0.26	0.007
34.93	0.16	0.25	0.26	0.22	0.006
41.28	0.23	0.26	0.26	0.25	0.006
47.63	0.19	0.23	0.29	0.24	0.006
53.98	-	-	-	-	-
60.33	-	-	-	-	-
66.68	-	-	-	-	-
73.03	-	-	-	-	-

MIX CPR10
Unit W. 144.02 (pcf)

Depth (mm)	NaCl (lb/yd^3) A	B	C	AVG	AVG. NaCl (%Conc)
3.18	45.22	37.53	41.91	41.55	1.069
9.53	25.40	22.54	29.95	25.96	0.668
15.88	9.66	9.03	9.32	9.33	0.240
22.23	3.65	2.56	2.32	2.84	0.073
28.58	1.00	0.70	0.57	0.76	0.019
34.93	0.63	0.33	0.24	0.40	0.010
41.28	0.40	0.34	0.27	0.34	0.009
47.63	0.30	0.20	0.25	0.25	0.006
53.98	-	-	-	-	-
60.33	-	-	-	-	-
66.68	-	-	-	-	-
73.03	-	-	-	-	-

MIX CPR11
Unit W. 142.82 (pcf)

Depth (mm)	NaCl (lb/yd^3) A	B	C	AVG	AVG. NaCl (%Conc)
3.18	44.08	58.04	48.73	50.28	1.304
9.53	30.68	34.27	36.17	33.71	0.874
15.88	14.20	10.90	13.39	12.83	0.333
22.23	3.51	2.22	6.46	4.06	0.105
28.58	0.51	0.78	1.62	0.97	0.025
34.93	0.25	0.26	0.89	0.47	0.012
41.28	0.26	0.22	0.32	0.27	0.007
47.63	0.24	0.27	0.24	0.25	0.007
53.98	-	-	-	-	-
60.33	-	-	-	-	-
66.68	-	-	-	-	-
73.03	-	-	-	-	-

MIX CPR12
Unit W. 139.58 (pcf)

Depth (mm)	NaCl (lb/yd^3) A	B	C	AVG	AVG. NaCl (%Conc)
3.18	69.23	49.49	57.57	58.77	1.559
9.53	40.87	32.62	31.39	34.96	0.928
15.88	29.83	26.07	25.37	27.09	0.719
22.23	20.95	18.91	19.07	19.64	0.521
28.58	15.93	13.84	12.72	14.16	0.376
34.93	8.29	8.15	6.45	7.63	0.202
41.28	4.34	1.58	2.12	2.68	0.071
47.63	1.80	0.28	0.42	0.83	0.022
53.98	-	-	-	-	-
60.33	-	-	-	-	-
66.68	-	-	-	-	-
73.03	-	-	-	-	-

Diffusion 5. 364-Day Bulk Diffusion Chloride Profile Testing Results (CPR13 to CPR20 Mixtures).

MIX CPR13
Unit W. 140.49 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	43.63	50.52	53.27	49.14	1.295
9.53	32.31	35.41	35.10	34.27	0.904
15.88	25.69	22.10	28.52	25.44	0.671
22.23	23.63	18.67	22.46	21.59	0.569
28.58	14.02	15.14	13.77	14.31	0.377
34.93	9.53	9.37	9.18	9.36	0.247
41.28	5.20	6.04	5.75	5.66	0.149
47.63	2.84	3.34	2.92	3.03	0.080
53.98	1.15	1.27	0.74	1.05	0.028
60.33	0.75	0.95	0.66	0.79	0.021
66.68	-	-	-	-	-
73.03	-	-	-	-	-

MIX CPR15
Unit W. 148.64 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	46.51	53.91	53.39	51.27	1.277
9.53	37.70	47.28	41.12	42.03	1.047
15.88	32.42	17.39	16.61	22.14	0.552
22.23	25.00	11.28	12.85	16.37	0.408
28.58	10.03	7.66	9.56	9.08	0.226
34.93	5.24	3.89	4.21	4.45	0.111
41.28	1.96	2.19	2.93	2.36	0.059
47.63	0.85	1.38	1.21	1.15	0.029
53.98	-	-	-	-	-
60.33	-	-	-	-	-
66.68	-	-	-	-	-
73.03	-	-	-	-	-

MIX CPR16
Unit W. 145.01 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	51.17	44.49	37.76	44.47	1.136
9.53	33.77	31.68	27.85	31.10	0.794
15.88	26.83	21.83	18.56	22.41	0.572
22.23	17.01	12.56	12.23	13.94	0.356
28.58	5.37	6.03	4.44	5.28	0.135
34.93	2.53	3.36	2.34	2.74	0.070
41.28	0.73	1.44	1.16	1.11	0.028
47.63	0.55	0.88	1.11	0.85	0.022
53.98	-	-	-	-	-
60.33	-	-	-	-	-
66.68	-	-	-	-	-
73.03	-	-	-	-	-

MIX CPR17
Unit W. 143.08 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	25.27	23.58	22.05	23.63	0.612
9.53	14.69	16.79	15.54	15.67	0.406
15.88	9.36	10.49	9.78	9.88	0.256
22.23	2.40	6.11	4.63	4.38	0.113
28.58	0.82	5.19	2.31	2.78	0.072
34.93	0.32	1.79	0.74	0.95	0.025
41.28	0.32	0.59	0.37	0.42	0.011
47.63	0.27	0.36	0.48	0.37	0.010
53.98	-	-	-	-	-
60.33	-	-	-	-	-
66.68	-	-	-	-	-
73.03	-	-	-	-	-

MIX CPR18
Unit W. 148.77 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	23.18	23.34	25.52	24.01	0.598
9.53	17.44	15.20	17.46	16.70	0.416
15.88	2.44	3.56	5.03	3.68	0.092
22.23	1.47	1.73	1.35	1.52	0.038
28.58	0.55	0.53	0.55	0.54	0.013
34.93	0.54	0.51	0.49	0.51	0.013
41.28	0.50	0.51	0.45	0.49	0.012
47.63	0.48	0.49	0.45	0.47	0.012
53.98	-	-	-	-	-
60.33	-	-	-	-	-
66.68	-	-	-	-	-
73.03	-	-	-	-	-

MIX CPR20
Unit W. 142.16 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	21.32	22.31	21.29	21.64	0.564
9.53	13.30	13.69	10.16	12.38	0.323
15.88	6.96	4.67	3.24	4.95	0.129
22.23	3.51	2.89	1.05	2.48	0.065
28.58	1.14	0.43	0.27	0.62	0.016
34.93	0.68	0.28	0.87	0.61	0.016
41.28	0.39	0.31	0.28	0.32	0.008
47.63	0.39	0.23	0.32	0.31	0.008
53.98	-	-	-	-	-
60.33	-	-	-	-	-
66.68	-	-	-	-	-
73.03	-	-	-	-	-

Diffusion 6. 364-Day Bulk Diffusion Chloride Profile Testing Results (CPR21 Mixture).

MIX CPR21

Unit W. 147.39 (pcf)

Depth	**NaCl (lb/yd^3)**				**AVG. NaCl**
(mm)	**A**	**B**	**C**	**AVG**	**(%Conc)**
3.18	32.78	24.58	25.70	27.69	0.696
9.53	22.95	20.17	13.72	18.95	0.476
15.88	5.27	8.62	3.70	5.86	0.147
22.23	0.94	2.44	1.23	1.54	0.039
28.58	0.40	0.47	0.37	0.41	0.010
34.93	0.42	0.33	0.30	0.35	0.009
41.28	0.32	0.31	0.34	0.32	0.008
47.63	0.46	0.35	0.33	0.38	0.009
53.98	-	-	-	-	-
60.33	-	-	-	-	-
66.68	-	-	-	-	-
73.03	-	-	-	-	-

Diffusion 7. 364-Day AASHTO T259 Ponding Test Chloride Profile Testing Results (CPR1 to CPR6 Mixtures).

MIX CPR1

Unit W. 140.62 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	7.62	9.18	9.43	8.74	0.230
9.53	6.09	7.07	7.48	6.88	0.181
15.88	6.79	6.80	6.62	6.74	0.177
22.23	4.56	6.82	5.22	5.53	0.146
28.58	3.70	3.93	2.68	3.44	0.090
34.93	1.92	2.44	1.71	2.02	0.053
41.28	1.00	1.27	0.90	1.05	0.028
47.63	0.42	0.42	0.24	0.36	0.010
53.98	0.21	0.16	0.18	0.18	0.005
60.33	0.21	0.22	0.18	0.20	0.005

MIX CPR2

Unit W. 144.62 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	6.61	8.51	7.09	7.40	0.190
9.53	3.80	5.23	4.41	4.48	0.115
15.88	1.99	2.96	2.65	2.53	0.065
22.23	0.68	0.91	0.92	0.83	0.021
28.58	0.30	0.47	0.36	0.37	0.010
34.93	0.27	0.36	0.30	0.31	0.008
41.28	-	-	-	-	-
47.63	-	-	-	-	-
53.98	-	-	-	-	-
60.33	-	-	-	-	-

MIX CPR3

Unit W. 140.40 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	5.62	8.09	6.50	6.74	0.178
9.53	4.32	6.52	4.93	5.25	0.139
15.88	3.59	5.29	4.28	4.39	0.116
22.23	2.52	4.06	2.73	3.10	0.082
28.58	1.14	2.18	1.28	1.53	0.040
34.93	0.40	0.76	0.35	0.50	0.013
41.28	-	-	-	-	-
47.63	-	-	-	-	-
53.98	-	-	-	-	-
60.33	-	-	-	-	-

MIX CPR4

Unit W. 142.32 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	4.87	4.71	5.17	4.92	0.128
9.53	0.77	0.70	0.87	0.78	0.020
15.88	0.31	0.38	0.33	0.34	0.009
22.23	0.29	0.28	0.30	0.29	0.008
28.58	0.28	0.27	0.28	0.27	0.007
34.93	0.28	0.29	0.27	0.28	0.007
41.28	-	-	-	-	-
47.63	-	-	-	-	-
53.98	-	-	-	-	-
60.33	-	-	-	-	-

MIX CPR5

Unit W. 144.32 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	6.26	5.22	7.53	6.34	0.163
9.53	2.45	1.87	3.02	2.45	0.063
15.88	0.73	0.62	0.73	0.69	0.018
22.23	0.25	0.23	0.27	0.25	0.006
28.58	0.27	0.23	0.20	0.23	0.006
34.93	0.19	0.20	0.25	0.21	0.005
41.28	-	-	-	-	-
47.63	-	-	-	-	-
53.98	-	-	-	-	-
60.33	-	-	-	-	-

MIX CPR6

Unit W. 140.52 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	16.49	15.36	14.03	15.29	0.403
9.53	10.10	9.95	9.73	9.93	0.262
15.88	5.92	6.69	5.26	5.96	0.157
22.23	2.09	3.51	2.40	2.67	0.070
28.58	0.74	1.24	0.58	0.85	0.022
34.93	0.19	0.37	0.30	0.28	0.007
41.28	-	-	-	-	-
47.63	-	-	-	-	-
53.98	-	-	-	-	-
60.33	-	-	-	-	-

Diffusion 8. 364-Day AASHTO T259 Ponding Test Chloride Profile Testing Results (CPR7 to CPR12 Mixtures).

MIX CPR7

Unit W. 143.72 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	9.39	10.08	20.80	13.42	0.346
9.53	2.54	2.90	5.92	3.79	0.098
15.88	0.83	0.69	1.80	1.11	0.029
22.23	0.26	0.29	0.32	0.29	0.007
28.58	0.29	0.29	0.22	0.27	0.007
34.93	0.28	0.21	0.21	0.23	0.006
41.28	-	-	-	-	-
47.63	-	-	-	-	-
53.98	-	-	-	-	-
60.33	-	-	-	-	-

MIX CPR8

Unit W. 139.72 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	24.57	9.77	16.29	16.87	0.447
9.53	9.95	7.46	10.05	9.15	0.243
15.88	3.90	5.00	5.29	4.73	0.125
22.23	0.88	1.29	1.13	1.10	0.029
28.58	0.41	0.63	0.95	0.66	0.018
34.93	0.36	0.36	0.39	0.37	0.010
41.28	-	-	-	-	-
47.63	-	-	-	-	-
53.98	-	-	-	-	-
60.33	-	-	-	-	-

MIX CPR9

Unit W. 145.22 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	10.68	10.20	9.90	10.26	0.262
9.53	2.78	2.72	2.35	2.62	0.067
15.88	0.78	0.79	0.68	0.75	0.019
22.23	0.22	0.26	0.20	0.23	0.006
28.58	0.15	0.22	0.15	0.17	0.004
34.93	0.17	0.19	0.16	0.17	0.004
41.28	0.17	0.15	0.15	0.15	0.004
47.63	0.19	0.16	0.13	0.16	0.004
53.98	-	-	-	-	-
60.33	-	-	-	-	-

MIX CPR10

Unit W. 144.02 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	10.06	7.91	6.81	8.26	0.212
9.53	2.22	1.75	1.01	1.66	0.043
15.88	0.26	0.24	0.31	0.27	0.007
22.23	0.36	0.17	0.23	0.25	0.006
28.58	0.20	0.17	0.20	0.19	0.005
34.93	0.17	0.16	0.18	0.17	0.004
41.28	0.19	0.16	0.16	0.17	0.004
47.63	0.17	0.17	0.16	0.16	0.004
53.98	-	-	-	-	-
60.33	-	-	-	-	-

MIX CPR11

Unit W. 142.82 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	14.59	13.82	14.68	14.36	0.372
9.53	4.41	5.38	4.76	4.85	0.126
15.88	0.60	1.30	1.42	1.11	0.029
22.23	0.31	0.43	0.47	0.40	0.010
28.58	0.25	0.25	0.24	0.25	0.006
34.93	0.24	0.24	0.23	0.24	0.006
41.28	0.24	0.23	0.19	0.22	0.006
47.63	0.25	0.24	0.21	0.23	0.006
53.98	-	-	-	-	-
60.33	-	-	-	-	-

MIX CPR12

Unit W. 139.58 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	10.02	8.08	9.83	9.31	0.247
9.53	3.84	2.87	4.28	3.66	0.097
15.88	1.43	1.14	1.46	1.34	0.036
22.23	0.25	0.25	0.23	0.24	0.006
28.58	0.16	0.16	0.14	0.15	0.004
34.93	0.18	0.16	0.15	0.16	0.004
41.28	0.17	0.15	0.14	0.15	0.004
47.63	0.14	0.16	0.14	0.15	0.004
53.98	-	-	-	-	-
60.33	-	-	-	-	-

Diffusion 9. 364-Day AASHTO T259 Ponding Test Chloride Profile Testing Results (CPR13 to CPR20 Mixtures).

MIX CPR13

Unit W. 140.49 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	11.41	11.58	9.98	10.99	0.290
9.53	9.31	10.79	8.43	9.51	0.251
15.88	7.09	9.51	6.99	7.86	0.207
22.23	4.70	7.25	4.62	5.52	0.146
28.58	1.82	5.72	1.83	3.12	0.082
34.93	0.79	3.11	0.75	1.55	0.041
41.28	0.29	0.80	0.31	0.47	0.012
47.63	0.35	0.37	0.30	0.34	0.009
53.98	0.29	0.29	0.28	0.29	0.008
60.33	0.37	0.52	0.27	0.38	0.010

MIX CPR15

Unit W. 148.64 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	15.49	5.70	19.22	13.47	0.336
9.53	13.26	1.75	15.46	10.16	0.253
15.88	11.32	0.57	9.94	7.28	0.181
22.23	8.47	0.48	4.67	4.54	0.113
28.58	7.05	0.51	3.21	3.59	0.089
34.93	4.43	0.48	0.68	1.86	0.046
41.28	0.67	0.50	0.46	0.54	0.014
47.63	0.52	0.47	0.42	0.47	0.012
53.98	-	-	-	-	-
60.33	-	-	-	-	-

MIX CPR16

Unit W. 145.01 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	8.92	4.55	9.15	7.54	0.193
9.53	6.03	1.44	6.19	4.55	0.116
15.88	3.31	0.61	2.47	2.13	0.054
22.23	1.07	0.34	0.92	0.77	0.020
28.58	-	-	-	-	-
34.93	-	-	-	-	-
41.28	-	-	-	-	-
47.63	-	-	-	-	-
53.98	-	-	-	-	-
60.33	-	-	-	-	-

MIX CPR17

Unit W. 143.08 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	6.90	7.46	10.11	8.16	0.211
9.53	2.59	2.78	2.80	2.72	0.070
15.88	1.02	0.93	0.83	0.92	0.024
22.23	0.37	0.37	0.34	0.36	0.009
28.58	-	-	-	-	-
34.93	-	-	-	-	-
41.28	-	-	-	-	-
47.63	-	-	-	-	-
53.98	-	-	-	-	-
60.33	-	-	-	-	-

MIX CPR18

Unit W. 148.77 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	4.53	3.48	3.96	3.99	0.099
9.53	0.71	0.55	0.72	0.66	0.016
15.88	0.33	0.35	0.34	0.34	0.008
22.23	0.32	0.34	0.34	0.33	0.008
28.58	-	-	-	-	-
34.93	-	-	-	-	-
41.28	-	-	-	-	-
47.63	-	-	-	-	-
53.98	-	-	-	-	-
60.33	-	-	-	-	-

MIX CPR20

Unit W. 142.16 (pcf)

Depth	NaCl (lb/yd^3)				AVG. NaCl
(mm)	A	B	C	AVG	(%Conc)
3.18	12.45	10.24	5.04	9.24	0.241
9.53	4.02	2.79	0.83	2.55	0.066
15.88	0.94	1.04	0.30	0.76	0.020
22.23	0.33	0.31	0.23	0.29	0.008
28.58	-	-	-	-	-
34.93	-	-	-	-	-
41.28	-	-	-	-	-
47.63	-	-	-	-	-
53.98	-	-	-	-	-
60.33	-	-	-	-	-

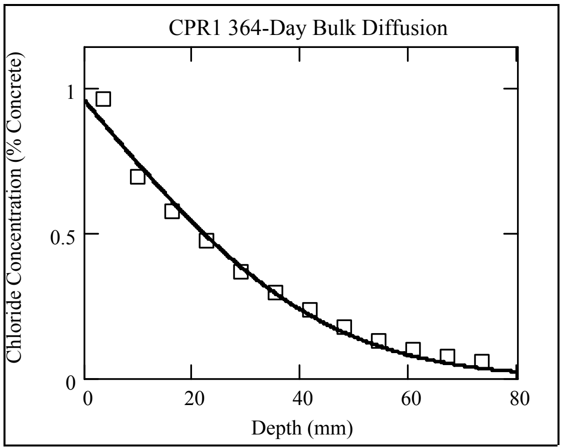
Diffusion 10. 364-Day AASHTO T259 Ponding Test Chloride Profile Testing Results (CPR21 Mixture).

MIX CPR21

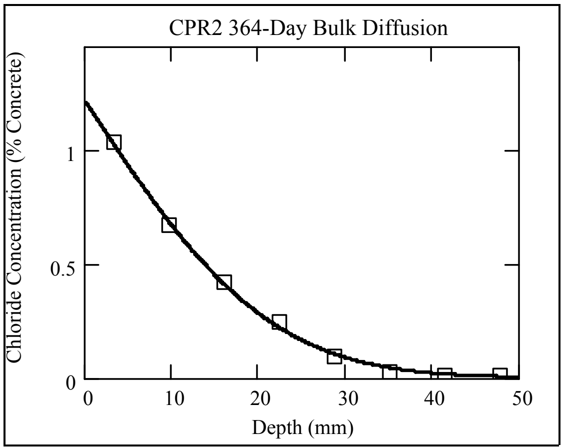
Unit W. 147.39 (pcf)

Depth	**NaCl (lb/yd^3)**				**AVG. NaCl**
(mm)	**A**	**B**	**C**	**AVG**	**(%Conc)**
3.18	2.36	4.33	2.29	3.00	0.075
9.53	0.48	0.86	0.44	0.59	0.015
15.88	0.42	0.45	0.37	0.41	0.010
22.23	0.41	0.41	0.34	0.39	0.010
28.58	-	-	-	-	-
34.93	-	-	-	-	-
41.28	-	-	-	-	-
47.63	-	-	-	-	-
53.98	-	-	-	-	-
60.33	-	-	-	-	-

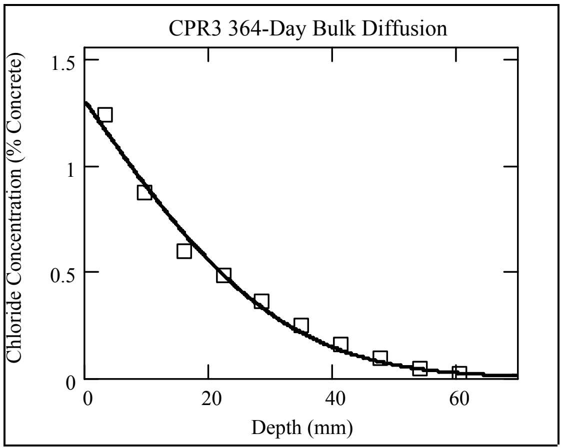
Diffusion 11. 364-Day Bulk Diffusion Coefficient Results (CPR1 to CPR6 Mixtures).


CPR1 364-Day Bulk Diffusion

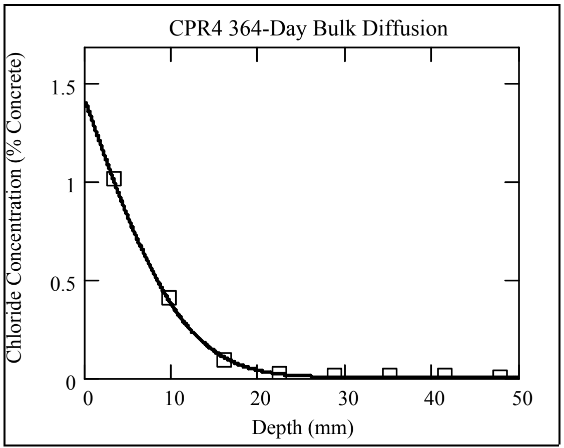
Diffusion(m^2/sec)	1.853E-11	**Background(% Con)**	0.004
Surface(% Con)	0.957	**R^2 Value**	0.9930


CPR2 364-Day Bulk Diffusion

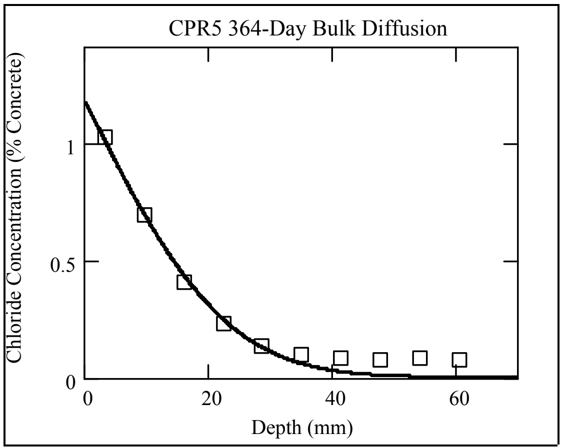
Diffusion(m^2/sec)	4.435E-12	**Background(% Con)**	0.002
Surface(% Con)	1.213	**R^2 Value**	0.9992


CPR3 364-Day Bulk Diffusion

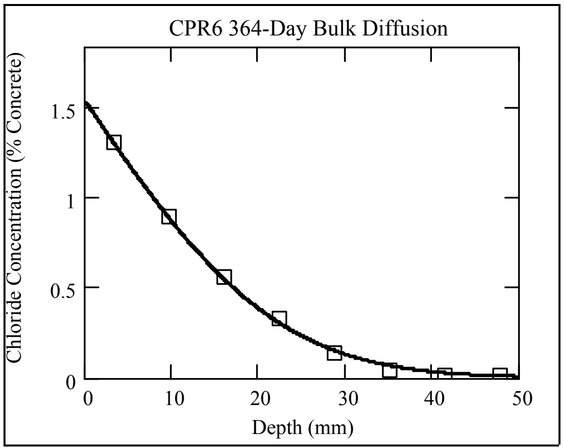
Diffusion(m^2/sec)	9.916E-12	**Background(% Con)**	0.003
Surface(% Con)	1.301	**R^2 Value**	0.9941


CPR4 364-Day Bulk Diffusion

Diffusion(m^2/sec)	1.256E-12	**Background(% Con)**	0.004
Surface(% Con)	1.408	**R^2 Value**	0.9998

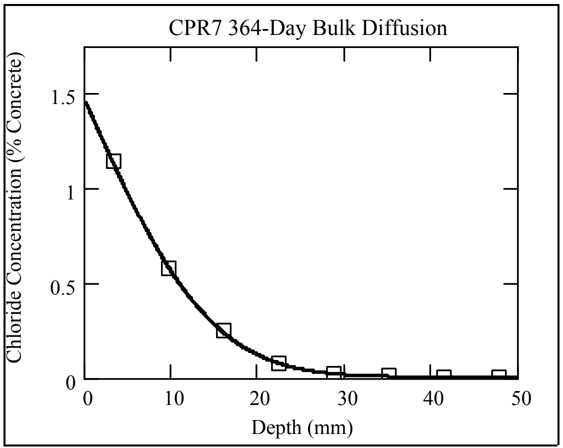

CPR5 364-Day Bulk Diffusion

Diffusion(m^2/sec)	5.025E-12	**Background(% Con)**	0.004
Surface(% Con)	1.185	**R^2 Value**	0.9947

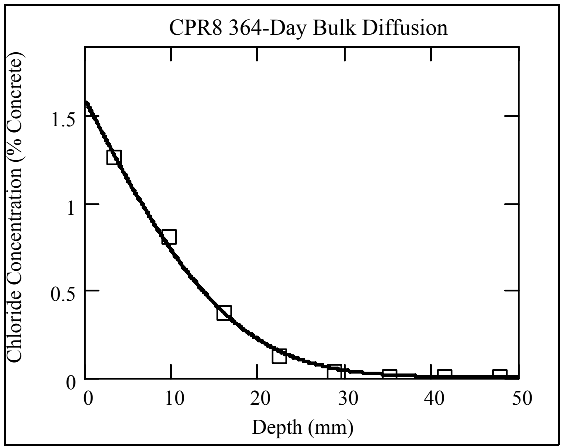

CPR6 364-Day Bulk Diffusion

Diffusion(m^2/sec)	4.777E-12	**Background(% Con)**	0.003
Surface(% Con)	1.538	**R^2 Value**	0.9996

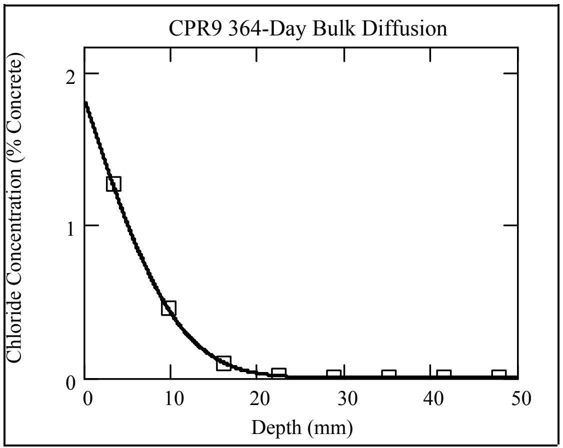
Diffusion 12. 364-Day Bulk Diffusion Coefficient Results (CPR7 to CPR12 Mixtures).



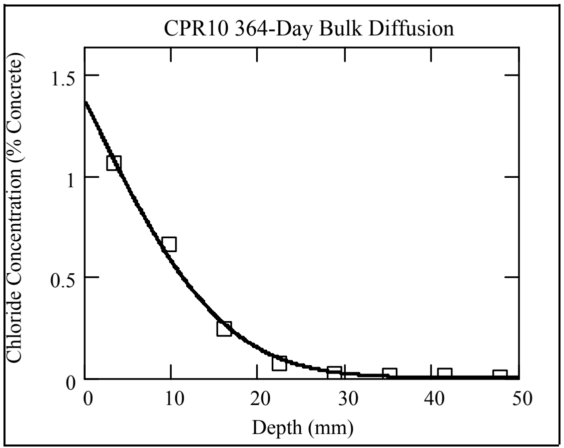
Diffusion(m^2/sec)	2.057E-12	**Background(% Con)**	0.006
Surface(% Con)	1.460	**R^2 Value**	0.9999



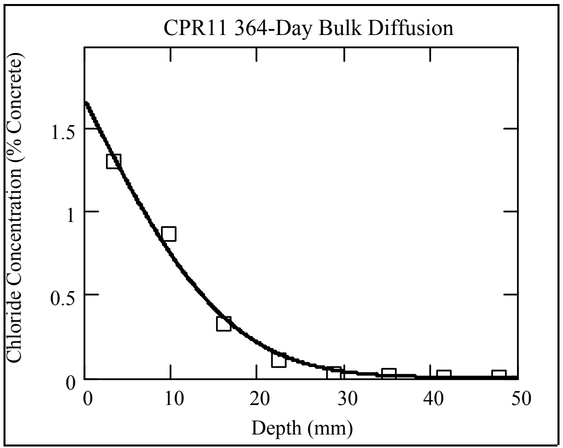
Diffusion(m^2/sec)	2.853E-12	**Background(% Con)**	0.003
Surface(% Con)	1.586	**R^2 Value**	0.9987



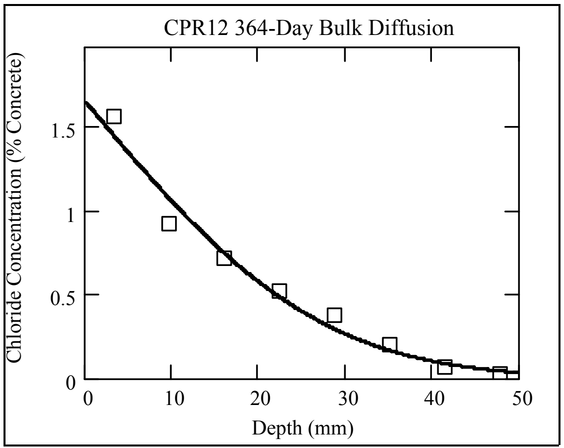
Diffusion(m^2/sec)	1.100E-12	**Background(% Con)**	0.002
Surface(% Con)	1.812	**R^2 Value**	1.0000



Diffusion(m^2/sec)	2.425E-12	**Background(% Con)**	0.002
Surface(% Con)	1.370	**R^2 Value**	0.9970

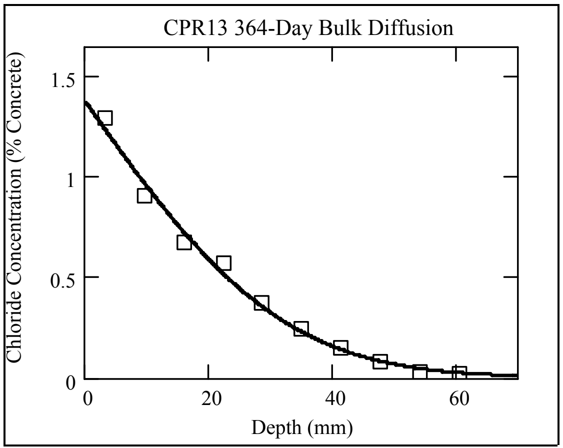


Diffusion(m^2/sec)	2.684E-12	**Background(% Con)**	0.005
Surface(% Con)	1.665	**R^2 Value**	0.9955

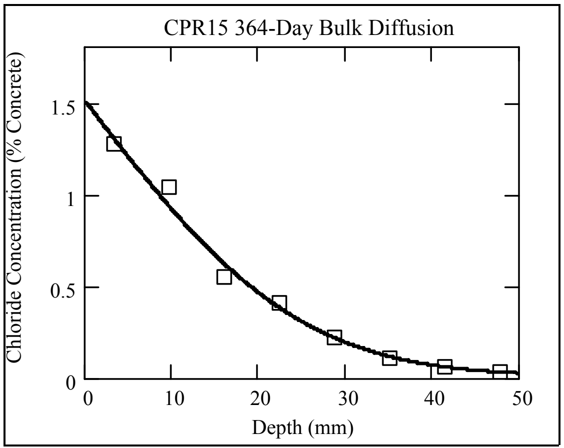


Diffusion(m^2/sec)	7.164E-12	**Background(% Con)**	0.004
Surface(% Con)	1.652	**R^2 Value**	0.9879

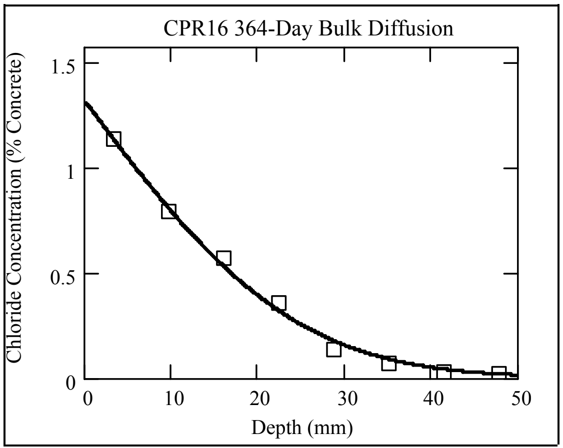
Diffusion 13. 364-Day Bulk Diffusion Coefficient Results (CPR13 to CPR20 Mixtures).



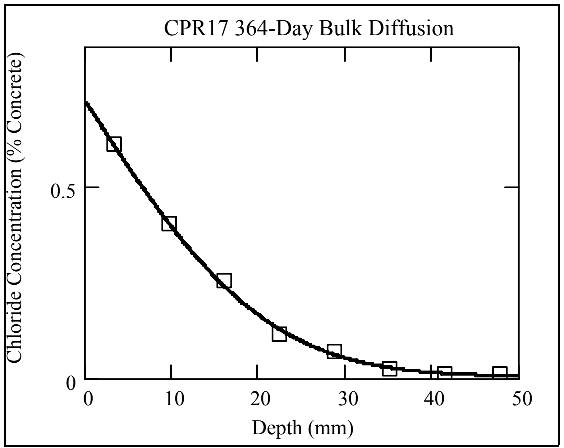
Diffusion(m^2/sec)	1.005E-11	**Background(% Con)**	0.005
Surface(% Con)	1.375	**R^2 Value**	0.9954



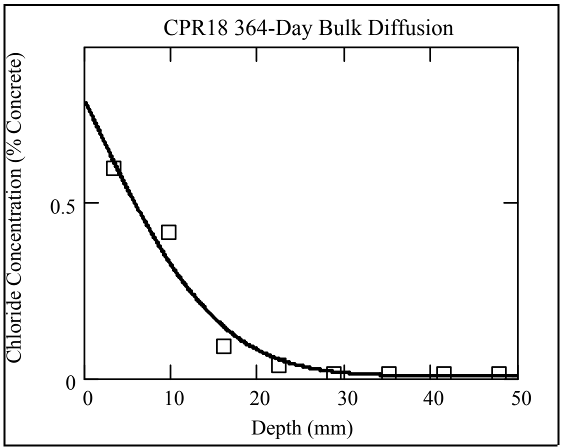
Diffusion(m^2/sec)	5.952E-12	**Background(% Con)**	0.013
Surface(% Con)	1.513	**R^2 Value**	0.9940



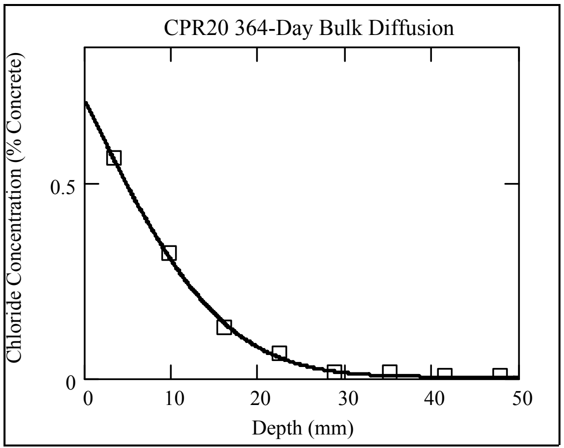
Diffusion(m^2/sec)	5.801E-12	**Background(% Con)**	0.003
Surface(% Con)	1.313	**R^2 Value**	0.9978



Diffusion(m^2/sec)	4.259E-12	**Background(% Con)**	0.005
Surface(% Con)	0.723	**R^2 Value**	0.9992

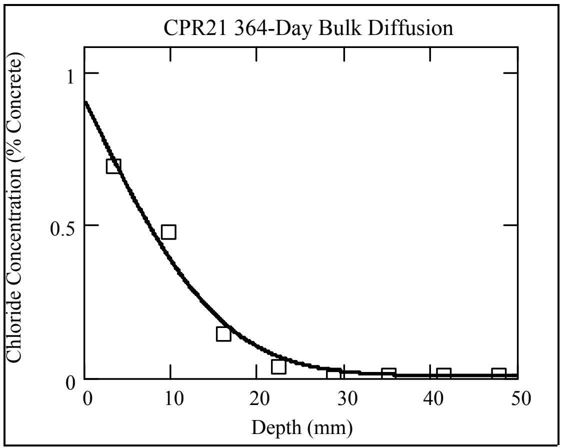


Diffusion(m^2/sec)	2.258E-12	**Background(% Con)**	0.006
Surface(% Con)	0.789	**R^2 Value**	0.9855



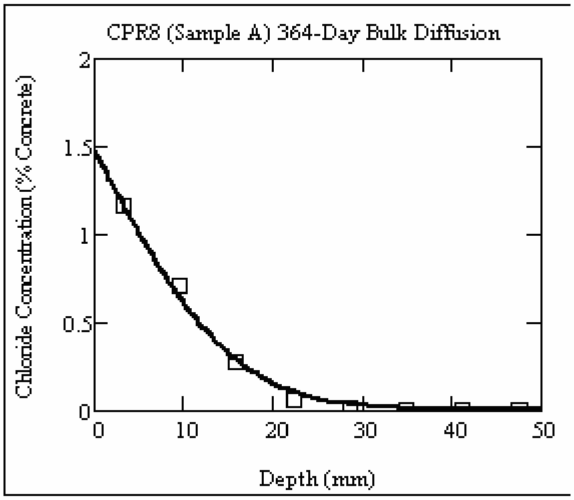
Diffusion(m^2/sec)	2.433E-12	**Background(% Con)**	0.003
Surface(% Con)	0.708	**R^2 Value**	0.9992

Diffusion 14. 364-Day Bulk Diffusion Coefficient Results (CPR21 Mixture).

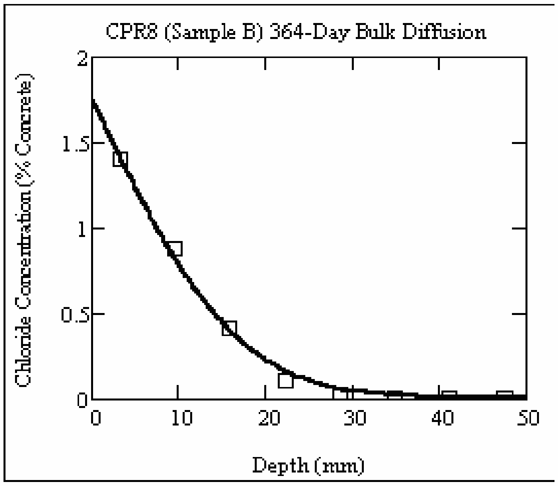


Diffusion(m^2/sec)	2.405E-12	**Background(% Con)**	0.008
Surface(% Con)	0.907	**R^2 Value**	0.9912

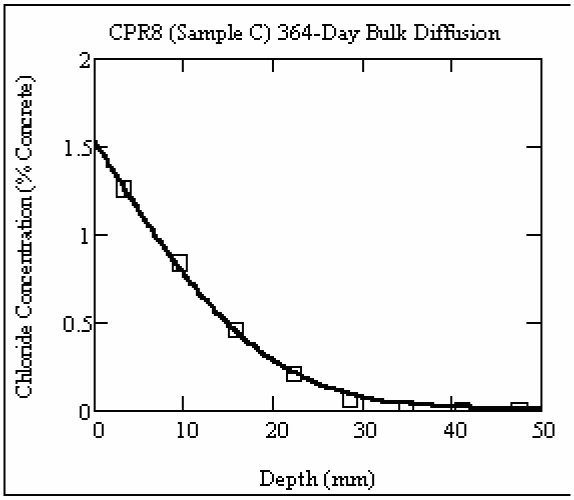
Diffusion 15. 364-Day Bulk Diffusion Coefficient Results for Each of the CPR8 Samples.



Diffusion(m^2/sec)	2.351E-12	**Background(% Con)**	0.003
Surface(% Con)	1.478	**R^2 Value**	0.9975

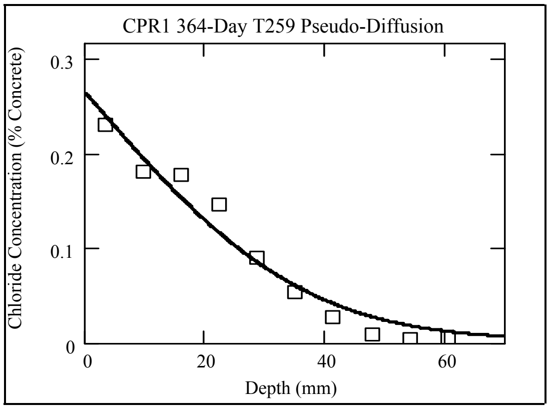


Diffusion(m^2/sec)	2.729E-12	**Background(% Con)**	0.003
Surface(% Con)	1.757	**R^2 Value**	0.9982

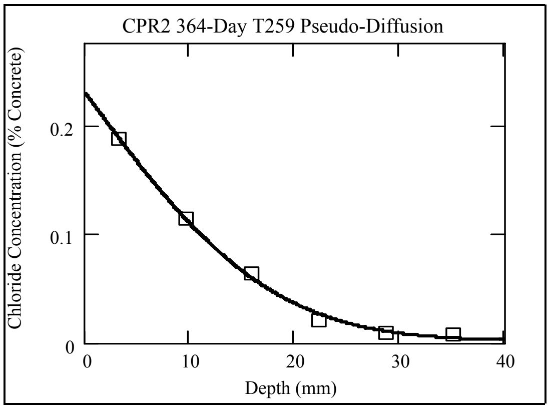


Diffusion(m^2/sec)	3.562E-12	**Background(% Con)**	0.003
Surface(% Con)	1.531	**R^2 Value**	0.9992

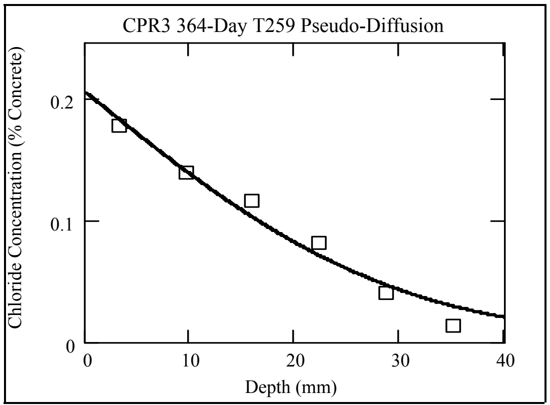
Diffusion 16. 364-Day AASHTO T259 Pseudo-Diffusion and Total Integral Chloride Content (CPR1 to CPR6 Mixtures).


CPR1 364-Day T259 Pseudo-Diffusion

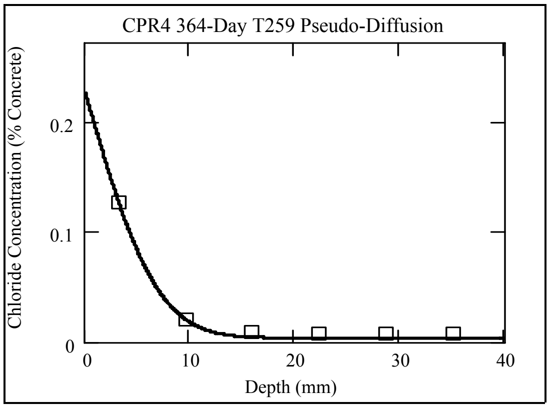
Diffusion(m^2/sec)	1.283E-11	**Background(% Con)**	0.004
Surface(% Con)	0.265	**R^2 Value**	0.9816
Total Integral Chloride Content (% Conc-mm)			5.9198


CPR2 364-Day T259 Pseudo-Diffusion

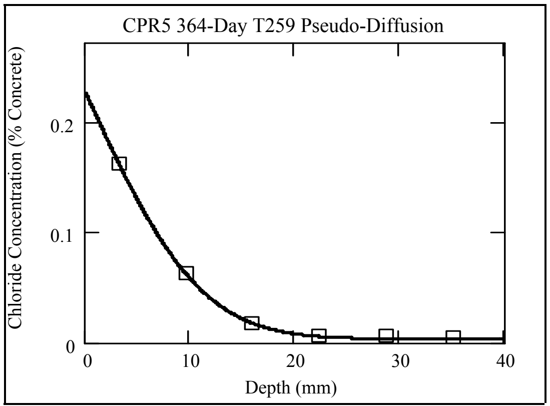
Diffusion(m^2/sec)	3.060E-12	**Background(% Con)**	0.002
Surface(% Con)	0.232	**R^2 Value**	0.9987
Total Integral Chloride Content (% Conc-mm)			2.5416


CPR3 364-Day T259 Pseudo-Diffusion

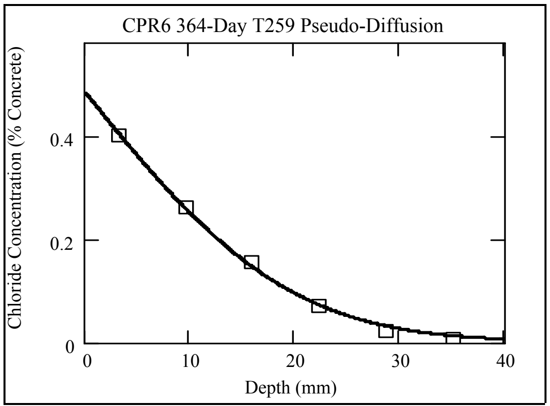
Diffusion(m^2/sec)	8.516E-12	**Background(% Con)**	0.003
Surface(% Con)	0.205	**R^2 Value**	0.9843
Total Integral Chloride Content (% Conc-mm)			3.725


CPR4 364-Day T259 Pseudo-Diffusion

Diffusion(m^2/sec)	4.563E-13	**Background(% Con)**	0.004
Surface(% Con)	0.228	**R^2 Value**	0.9995
Total Integral Chloride Content (% Conc-mm)			0.9572

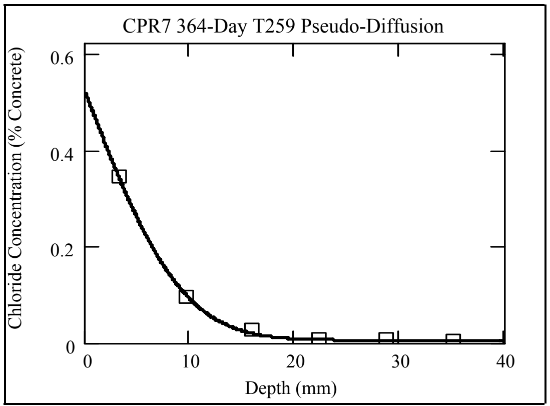

CPR5 364-Day T259 Pseudo-Diffusion

Diffusion(m^2/sec)	1.162E-12	**Background(% Con)**	0.004
Surface(% Con)	0.227	**R^2 Value**	0.9999
Total Integral Chloride Content (% Conc-mm)			1.527

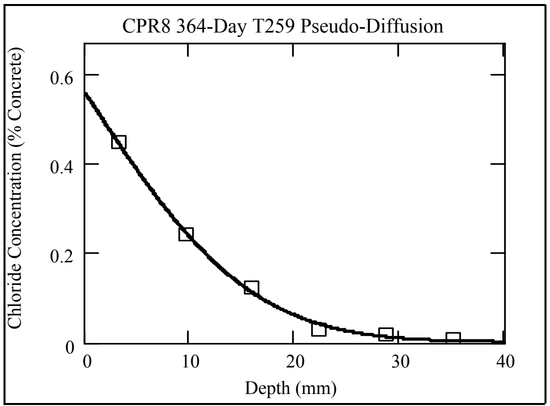

CPR6 364-Day T259 Pseudo-Diffusion

Diffusion(m^2/sec)	3.724E-12	**Background(% Con)**	0.003
Surface(% Con)	0.485	**R^2 Value**	0.9991
Total Integral Chloride Content (% Conc-mm)			5.8909

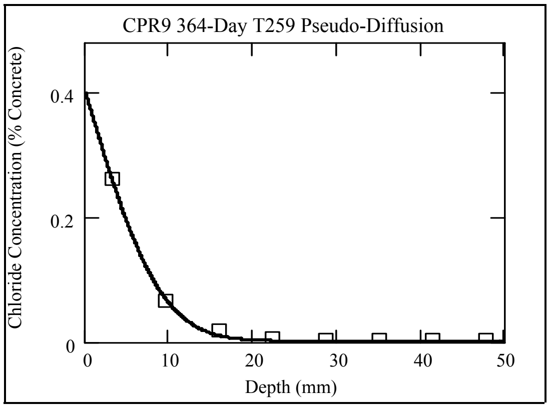
Diffusion 17. 364-Day AASHTO T259 Pseudo-Diffusion and Total Integral Chloride Content (CPR7 to CPR12 Mixtures).



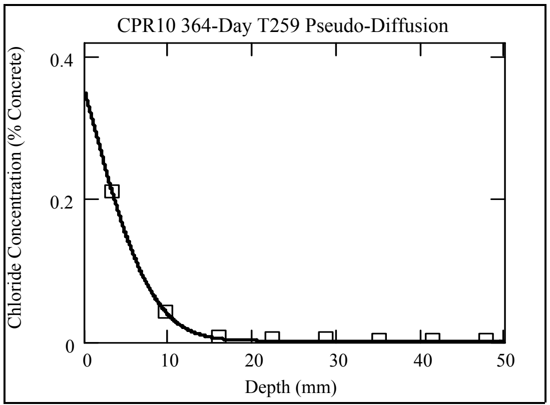
Diffusion(m^2/sec)	8.190E-13	**Background(% Con)**	0.006
Surface(% Con)	0.521	**R^2 Value**	0.9996
Total Integral Chloride Content (% Conc-mm)			2.9512



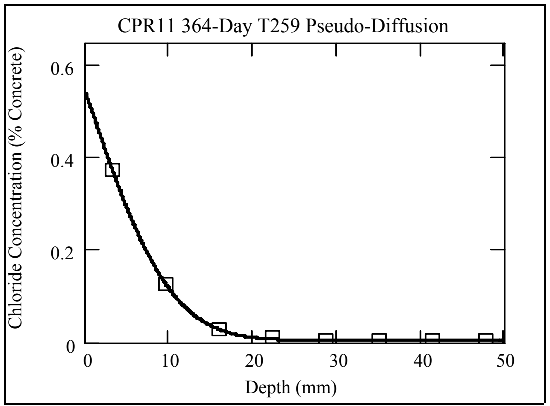
Diffusion(m^2/sec)	2.429E-12	**Background(% Con)**	0.003
Surface(% Con)	0.559	**R^2 Value**	0.9987
Total Integral Chloride Content (% Conc-mm)			5.489



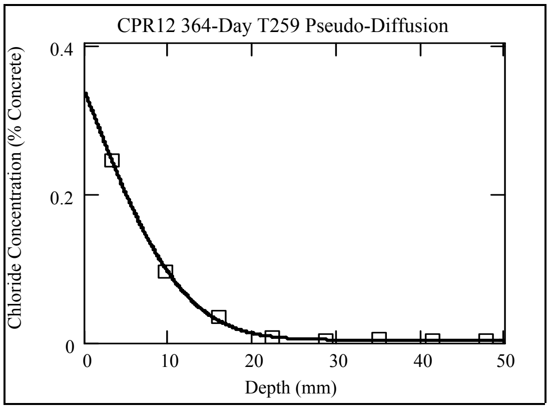
Diffusion(m^2/sec)	7.645E-13	**Background(% Con)**	0.002
Surface(% Con)	0.403	**R^2 Value**	0.9995
Total Integral Chloride Content (% Conc-mm)			2.2164



Diffusion(m^2/sec)	5.899E-13	**Background(% Con)**	0.002
Surface(% Con)	0.351	**R^2 Value**	0.9999
Total Integral Chloride Content (% Conc-mm)			1.6977

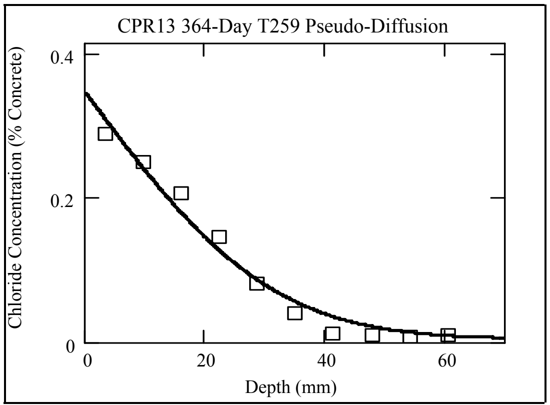


Diffusion(m^2/sec)	9.895E-13	**Background(% Con)**	0.005
Surface(% Con)	0.539	**R^2 Value**	1.0000
Total Integral Chloride Content (% Conc-mm)			3.3657

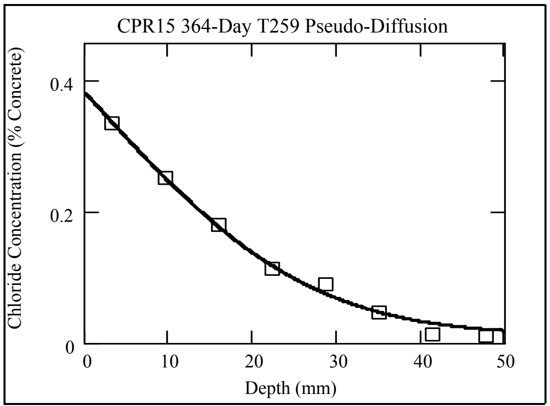


Diffusion(m^2/sec)	1.290E-12	**Background(% Con)**	0.004
Surface(% Con)	0.338	**R^2 Value**	0.9995
Total Integral Chloride Content (% Conc-mm)			2.4049

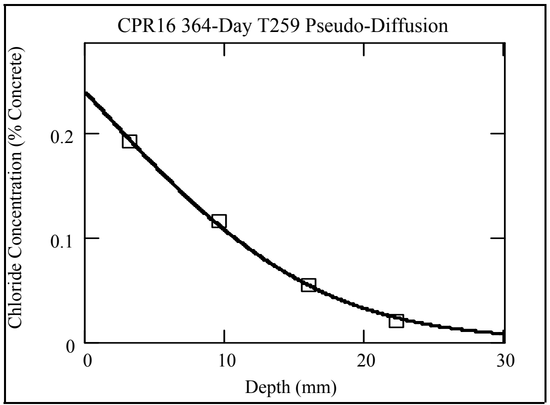
Diffusion 18. 364-Day AASHTO T259 Pseudo-Diffusion and Total Integral Chloride Content (CPR13 to CPR20 Mixtures).



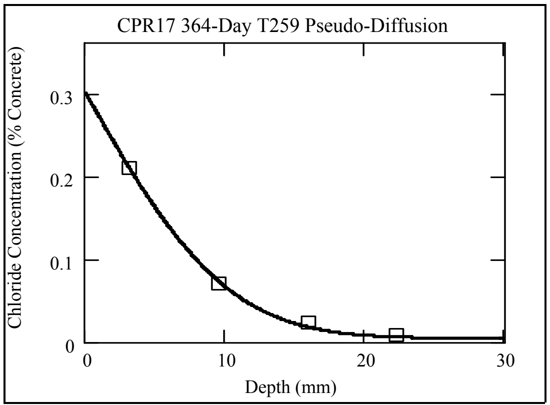
Diffusion(m^2/sec)	9.408E-12	**Background(% Con)**	0.005
Surface(% Con)	0.347	**R^2 Value**	0.9891
Total Integral Chloride Content (% Conc-mm)			6.6418



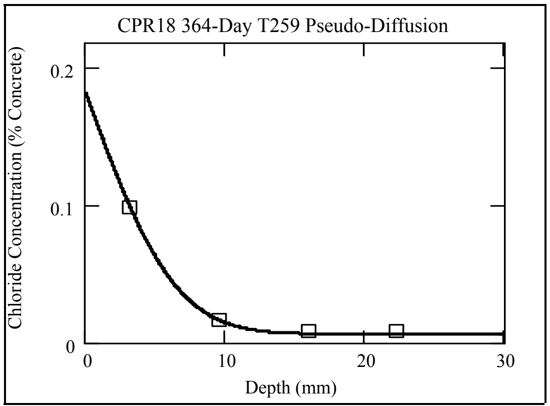
Diffusion(m^2/sec)	6.869E-12	**Background(% Con)**	0.013
Surface(% Con)	0.383	**R^2 Value**	0.9972
Total Integral Chloride Content (% Conc-mm)			6.1379



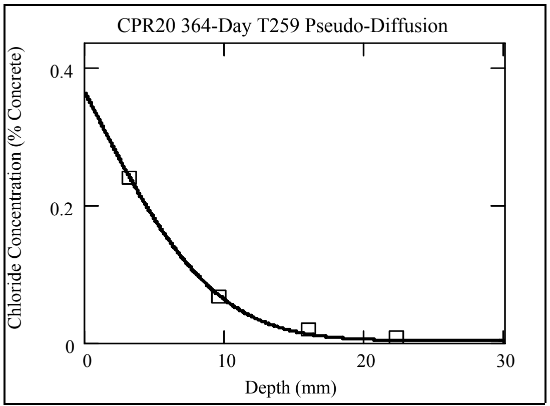
Diffusion(m^2/sec)	2.646E-12	**Background(% Con)**	0.003
Surface(% Con)	0.240	**R^2 Value**	0.9992
Total Integral Chloride Content (% Conc-mm)			2.4407



Diffusion(m^2/sec)	1.009E-12	**Background(% Con)**	0.005
Surface(% Con)	0.303	**R^2 Value**	0.9993
Total Integral Chloride Content (% Conc-mm)			1.8947

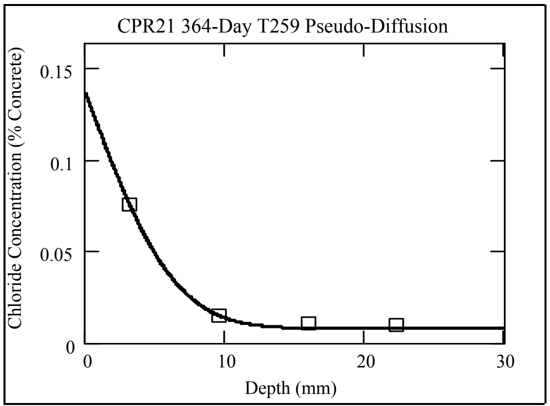


Diffusion(m^2/sec)	3.993E-13	**Background(% Con)**	0.006
Surface(% Con)	0.183	**R^2 Value**	0.9998
Total Integral Chloride Content (% Conc-mm)			0.7053



Diffusion(m^2/sec)	8.158E-13	**Background(% Con)**	0.003
Surface(% Con)	0.364	**R^2 Value**	0.9994
Total Integral Chloride Content (% Conc-mm)			2.0608

Diffusion 19. 364-Day AASHTO T259 Pseudo-Diffusion and Total Integral Chloride Content (CPR21 Mixture).



Diffusion(m^2/sec)	3.919E-13	**Background(% Con)**	0.008
Surface(% Con)	0.137	**R^2 Value**	0.9996
Total Integral Chloride Content (% Conc-mm)			0.5103

Diffusion 20. Summary Table of Long-Term Diffusion Test Results.

Mixture Name	364-Day AASHTO T259 Total Integral Chloride Content (%Concrete-mm)	364-Day AASHTO T259 Pseudo-Diffusion Coefficient ($x10^{-12}$) (m^2/sec)	364-Day Bulk Diffusion Coefficient ($x10^{-12}$) (m^2/sec)
CPR1	5.9198	12.8324	18.5310
CPR2	2.5416	3.0599	4.4347
CPR3	3.7250	8.5161	9.9158
CPR4	0.9572	0.4563	1.2560
CPR5	1.5270	1.1619	5.0250
CPR6	5.8909	3.7239	4.7765
CPR7	2.9512	0.8190	2.0572
CPR8	5.4890	2.4287	2.8534
CPR9	2.2164	0.7645	1.1001
CPR10	1.6977	0.5899	2.4254
CPR11	3.3657	0.9895	2.6841
CPR12	2.4049	1.2899	7.1644
CPR13	6.6418	9.4077	10.0530
CPR15	6.1379	6.8692	5.9518
CPR16	2.4407	2.6462	5.8011
CPR17	1.8947	1.0087	4.2591
CPR18	0.7053	0.3993	2.2585
CPR20	2.0608	0.8158	2.4332
CPR21	0.5103	0.3919	2.4054

APPENDIX C

SHORT-TERM ELECTRICAL TEST DATA AND ANALYSIS RESULTS.

Appendix Table of Contents

Elect. Tests 1. RCP Coulombs Testing Results (CPR1 to CPR10 Mixtures).

MIX CPR1

Testing Age	RCP (Coulombs)			
(Days)	A	B	C	AVG.
14	8719	8965	8780	8821
28	6917	6644	6847	6803
56	6952	8411	7207	7523
91	4676	5054	5599	5110
182	6047	5801	6056	5968
364	4922	4660	-	4791

MIX CPR2

Testing Age	RCP (Coulombs)			
(Days)	A	B	C	AVG.
14	5054	5001	5291	5115
28	3753	4333	3779	3955
56	3779	3858	4263	3967
91	3076	3770	4131	3659
182	2883	2883	2584	2783
364	2684	3011	3060	2918

MIX CPR3

Testing Age	RCP (Coulombs)			
(Days)	A	B	C	AVG.
14	11689	12568	13535	12597
28	9580	9141	9113	9278
56	8640	10107	6978	8575
91	8042	7181	7110	7444
182	6759	6003	5933	6232
364	4627	5111	4050	4596

MIX CPR4

Testing Age	RCP (Coulombs)			
(Days)	A	B	C	AVG.
14	1450	1248	1380	1359
28	781	806	757	781
56	540	514	448	501
91	408	460	388	419
182	386	359	396	380
364	309	300	268	292

MIX CPR5

Testing Age	RCP (Coulombs)			
(Days)	A	B	C	AVG.
14	7348	7269	8877	7831
28	5537	5686	5414	5546
56	2645	2645	2426	2572
91	1775	1723	1749	1749
182	1213	1195	1283	1230
364	862	792	753	802

MIX CPR6

Testing Age	RCP (Coulombs)			
(Days)	A	B	C	AVG.
14	8244	8033	6785	7687
28	6548	8648	7699	7632
56	4184	4368	4395	4316
91	2979	3120	2900	3000
182	4400	2992	4334	3909
364	1371	1520	1564	1485

MIX CPR7

Testing Age	RCP (Coulombs)			
(Days)	A	B	C	AVG.
14	2065	1942	2145	2051
28	1371	1485	1248	1368
56	984	1055	1055	1031
91	858	719	976	851
182	1027	887	0	957
364	791	721	0	756

MIX CPR8

Testing Age	RCP (Coulombs)			
(Days)	A	B	C	AVG.
14	2373	2408	2426	2402
28	1582	1397	1468	1482
56	1011	1002	1090	1034
91	967	1037	1099	1034
182	814	989	0	902
364	863	797	0	830

MIX CPR9

Testing Age	RCP (Coulombs)			
(Days)	A	B	C	AVG.
14	1090	1169	896	1052
28	1063	821	949	944
56	834	830	888	851
91	819	786	923	843
182	719	738	0	729
364	490	533	0	512

MIX CPR10

Testing Age	RCP (Coulombs)			
(Days)	A	B	C	AVG.
14	1362	1362	1318	1347
28	1178	1362	1213	1251
56	923	905	838	889
91	805	878	949	877
182	577	657	0	617
364	349	393	0	371

Elect. Tests 2. RCP Coulombs Testing Results (CPR11 to CPR21 Mixtures).

MIX CPR11

Testing Age	RCP (Coulombs)			
(Days)	**A**	**B**	**C**	**AVG.**
14	2610	2988	2979	2859
28	2215	2496	1969	2227
56	1679	1740	1723	1714
91	1564	1635	1854	1684
182	1222	1325	0	1274
364	1103	983	0	1043

MIX CPR12

Testing Age	RCP (Coulombs)			
(Days)	**A**	**B**	**C**	**AVG.**
14	12217	13887	12744	12949
28	5186	6363	8631	6727
56	5871	5915	6064	5950
91	5655	4484	5207	5115
182	4604	4436	0	4520
364	3618	3727	0	3673

MIX CPR13

Testing Age	RCP (Coulombs)			
(Days)	**A**	**B**	**C**	**AVG.**
14	8288	7058	7427	7591
28	5669	5836	6820	6108
56	5098	5713	5537	5449
91	4421	4913	4720	4685
182	4166	4184	3955	4102
364	4192	4488	0	4340

MIX CPR15

Testing Age	RCP (Coulombs)			
(Days)	**A**	**B**	**C**	**AVG.**
14	9141	7761	0	8451
28	7014	8156	0	7585
56	5774	5115	2821	4570
91	3568	4148	4412	4043
182	2769	2329	2566	2555
364	1814	1794	1839	1816

MIX CPR16

Testing Age	RCP (Coulombs)			
(Days)	**A**	**B**	**C**	**AVG.**
14	3964	5704	5001	4890
28	3894	4263	3727	3961
56	3261	2742	2610	2871
91	2092	2206	2224	2174
182	1538	1195	1090	1274
364	1180	1031	0	1106

MIX CPR17

Testing Age	RCP (Coulombs)			
(Days)	**A**	**B**	**C**	**AVG.**
14	5010	5423	0	5217
28	5036	3542	3234	3937
56	2303	2268	2162	2244
91	1793	2347	2118	2086
182	1644	1283	1626	1518
364	1175	1579	1508	1421

MIX CPR18

Testing Age	RCP (Coulombs)			
(Days)	**A**	**B**	**C**	**AVG.**
14	6680	7277	0	6979
28	3252	3032	0	3142
56	1591	1740	1652	1661
91	1160	1134	984	1093
182	544	621	588	584
364	329	357	306	331

MIX CPR20

Testing Age	RCP (Coulombs)			
(Days)	**A**	**B**	**C**	**AVG.**
14	4201	4904	0	4553
28	3173	3691	2997	3287
56	2250	1863	1960	2024
91	1477	1301	1547	1442
182	867	923	914	901
364	891	732	882	835

MIX CPR21

Testing Age	RCP (Coulombs)			
(Days)	**A**	**B**	**C**	**AVG.**
14	7427	7708	0	7568
28	4377	5502	0	4940
56	2347	2575	2461	2461
91	1510	1646	1529	1562
182	712	914	888	838
364	390	432	453	425

Elect. Tests 3. SR (Lime Cured) Testing Results (CPR1 to CPR8 Mixtures).

MIX CPR1

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	5.5	5.1	5.2	5.3
28	6.0	5.9	5.9	5.9
56	6.8	6.6	6.8	6.7
91	7.9	7.4	7.4	7.6
182	9.3	8.7	9.3	9.1
364	11.4	12.2	12.5	12.0
454	11.2	12.4	13.4	12.4
544	11.1	10.3	10.0	10.4

MIX CPR2

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	8.0	7.3	6.7	7.3
28	8.9	8.5	7.4	8.3
56	10.1	9.3	8.4	9.3
91	11.1	10.0	10.4	10.5
182	13.5	13.1	11.9	12.8
364	14.6	13.6	12.3	13.5
454	15.8	18.0	16.0	16.6
544	13.3	14.7	13.5	13.8

MIX CPR3

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	5.2	4.7	4.9	5.0
28	5.8	5.2	5.5	5.5
56	6.4	5.8	6.2	6.2
91	7.6	6.3	6.8	6.9
182	8.7	8.7	8.5	8.6
364	9.0	8.6	9.2	8.9
454	10.1	9.4	9.2	9.6
544	8.7	7.8	8.4	8.3

MIX CPR4

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	18.6	18.8	17.5	18.3
28	33.4	34.5	31.5	33.1
56	49.1	51.9	44.3	48.4
91	59.8	63.1	54.9	59.3
182	77.2	81.4	72.2	76.9
364	93.3	91.6	83.3	89.4
454	107.0	115.3	102.2	108.2
544	93.5	98.1	87.1	92.9

MIX CPR5

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	5.9	6.1	5.7	5.9
28	7.6	8.0	7.1	7.6
56	11.1	11.6	10.5	11.1
91	14.9	15.5	14.3	14.9
182	26.6	26.6	22.8	25.3
364	37.5	40.3	36.7	38.2
454	45.6	43.2	37.0	41.9
544	37.7	40.1	35.2	37.6

MIX CPR6

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	5.9	6.1	6.2	6.1
28	7.1	7.2	7.4	7.2
56	9.2	9.4	9.7	9.5
91	11.4	11.5	11.7	11.5
182	15.7	15.2	16.3	15.7
364	22.3	22.1	22.3	22.2
454	22.6	22.3	23.0	22.6
544	24.8	23.7	24.8	24.4

MIX CPR7

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	10.3	10.6	10.7	10.5
28	20.1	19.7	21.1	20.3
56	35.8	36.1	37.7	36.5
91	39.3	40.2	43.7	41.1
182	44.3	45.6	47.8	45.9
364	42.1	45.9	46.0	44.6
454	40.9	41.2	42.2	41.4
544	40.4	40.7	41.1	40.7

MIX CPR8

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	8.4	8.3	8.4	8.4
28	16.1	16.0	16.5	16.2
56	27.7	27.4	28.6	27.9
91	34.8	34.9	34.1	34.6
182	43.0	42.4	44.3	43.2
364	47.7	45.3	47.4	46.8
454	48.4	47.7	48.3	48.1
544	50.8	50.9	51.4	51.0

Elect. Tests 4. SR (Lime Cured) Testing Results (CPR9 to CPR17 Mixtures).

MIX CPR9

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	28.8	26.8	28.6	28.1
28	30.3	28.6	30.4	29.8
56	36.6	35.8	39.5	37.3
91	38.7	37.1	42.0	39.3
182	43.8	41.6	44.8	43.4
364	50.3	49.8	52.1	50.7
454	44.4	42.0	49.5	45.3
544	48.9	46.7	53.7	49.8

MIX CPR10

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	22.2	22.6	23.2	22.6
28	21.0	23.0	24.0	22.7
56	29.7	29.8	32.7	30.7
91	30.7	31.1	34.7	32.1
182	38.1	40.6	45.2	41.3
364	54.2	52.9	58.4	55.1
454	54.8	53.4	60.0	56.1
544	58.7	61.6	67.9	62.7

MIX CPR11

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	11.3	10.4	10.7	10.8
28	16.0	14.5	14.4	15.0
56	20.4	18.5	18.5	19.1
91	22.4	19.8	20.4	20.9
182	26.4	23.9	23.8	24.7
364	29.7	27.9	29.0	28.9
454	31.0	27.6	28.9	29.1
544	31.8	29.0	30.9	30.6

MIX CPR12

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	9.2	9.5	8.4	9.0
28	10.3	10.9	9.6	10.3
56	10.8	12.2	10.7	11.2
91	11.7	12.3	11.0	11.6
182	12.7	14.0	12.4	13.0
364	13.7	16.0	14.3	14.7
454	14.2	15.5	14.4	14.7
544	14.1	15.4	13.4	14.3

MIX CPR13

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	6.8	6.3	6.8	6.6
28	7.3	6.6	7.2	7.0
56	8.2	7.5	8.1	7.9
91	8.9	8.4	8.8	8.7
182	10.9	10.5	11.1	10.8
364	11.0	10.3	11.2	10.8
454	12.2	10.9	11.2	11.5
544	14.1	12.2	13.1	13.1

MIX CPR15

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	4.4	3.9	3.9	4.0
28	8.5	8.9	8.7	8.7
56	8.4	8.5	8.4	8.5
91	10.1	10.2	10.6	10.3
182	14.0	16.2	15.4	15.2
364	20.5	23.4	23.4	22.4
454	23.6	25.2	25.9	24.9
544	24.9	28.4	26.1	26.5

MIX CPR16

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	6.8	6.8	7.2	6.9
28	7.2	7.6	7.9	7.6
56	9.2	9.6	9.7	9.5
91	13.3	14.6	13.1	13.7
182	21.7	23.9	21.6	22.4
364	30.5	40.7	40.0	37.1
454	30.5	38.2	33.3	34.0
544	35.9	47.5	41.4	41.6

MIX CPR17

Testing Age	SR (Lime Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	6.3	5.5	5.6	5.8
28	8.9	8.6	8.6	8.7
56	12.6	12.3	12.0	12.3
91	16.6	16.5	16.1	16.4
182	24.0	24.8	23.6	24.1
364	31.3	34.0	36.1	33.8
454	33.3	34.0	33.1	33.4
544	32.4	35.6	34.6	34.2

Elect. Tests 5. SR (Lime Cured) Testing Results (CPR18 to CPR21 Mixtures).

MIX CPR18

Testing Age	**SR (Lime Cured) (kΩ.cm)**			
(Days)	**A**	**B**	**C**	**AVG.**
14	7.7	7.3	7.0	7.3
28	11.0	11.3	10.9	11.0
56	18.6	19.1	19.1	18.9
91	29.8	30.2	27.9	29.3
182	57.3	57.0	52.7	55.6
364	92.9	90.8	83.4	89.1
454	97.5	95.1	91.0	94.5
544	106.3	99.3	100.7	102.1

MIX CPR20

Testing Age	**SR (Lime Cured) (kΩ.cm)**			
(Days)	**A**	**B**	**C**	**AVG.**
14	5.6	5.5	7.0	6.0
28	10.8	11.9	13.3	12.0
56	15.3	15.5	15.6	15.5
91	20.2	20.4	20.6	20.4
182	31.2	31.1	30.4	30.9
364	43.7	42.7	47.8	44.7
454	46.1	46.6	43.7	45.4
544	45.9	45.1	43.4	44.8

MIX CPR21

Testing Age	**SR (Lime Cured) (kΩ.cm)**			
(Days)	**A**	**B**	**C**	**AVG.**
14	5.1	5.2	5.0	5.1
28	9.5	9.7	9.8	9.7
56	15.4	14.6	13.8	14.6
91	23.6	22.3	24.7	23.5
182	20.9	37.0	42.7	33.5
364	65.7	63.6	67.2	65.5
454	70.2	63.9	68.5	67.5
544	77.5	71.4	77.9	75.6

Elect. Tests 6. SR (Moist Cured) Testing Results (CPR1 to CPR8 Mixtures).

MIX CPR1

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	6.5	5.8	6.1	6.1
28	7.2	6.5	6.9	6.9
56	7.9	6.9	7.9	7.5
91	7.8	7.4	8.2	7.8
182	9.1	8.6	9.6	9.1
364	10.0	8.9	9.9	9.6
454	11.8	10.2	11.8	11.3
544	10.9	9.8	11.1	10.6

MIX CPR2

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	9.0	8.0	8.6	8.5
28	9.9	9.0	9.8	9.5
56	10.6	9.6	10.2	10.1
91	11.2	10.5	10.6	10.8
182	12.2	11.0	11.8	11.7
364	13.1	11.7	12.9	12.6
454	15.7	13.6	13.5	14.3
544	14.7	12.9	14.2	13.9

MIX CPR3

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	5.4	5.9	5.3	5.5
28	5.7	6.4	5.7	5.9
56	5.8	6.8	6.1	6.2
91	6.4	7.1	6.4	6.6
182	6.6	7.7	7.1	7.1
364	7.5	7.8	6.3	7.2
454	9.1	10.0	9.3	9.4
544	8.4	9.5	8.8	8.9

MIX CPR4

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	25.3	25.5	26.4	25.7
28	44.6	45.2	44.7	44.8
56	63.3	63.5	64.8	63.8
91	79.1	76.1	78.9	78.0
182	81.2	80.1	82.1	81.1
364	88.7	90.7	89.6	89.7
454	110.4	113.9	112.1	112.1
544	107.5	106.8	105.1	106.5

MIX CPR5

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	6.2	6.3	6.4	6.3
28	8.0	8.1	8.4	8.1
56	12.4	12.6	12.7	12.6
91	17.9	18.5	19.2	18.5
182	27.6	29.0	29.2	28.6
364	33.4	35.9	35.7	35.0
454	45.6	47.4	49.1	47.3
544	44.3	45.2	46.9	45.4

MIX CPR6

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	5.8	5.8	6.2	5.9
28	7.0	6.9	7.5	7.2
56	9.6	9.4	10.0	9.6
91	12.3	12.2	13.6	12.7
182	17.7	17.6	19.7	18.3
364	22.1	23.2	25.7	23.7
454	27.3	26.6	26.7	26.9
544	29.7	28.2	27.6	28.5

MIX CPR7

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	16.8	16.4	16.7	16.6
28	29.4	28.1	28.6	28.7
56	40.1	37.5	38.9	38.8
91	43.2	39.2	39.8	40.7
182	43.1	40.2	40.5	41.3
364	42.7	41.7	41.8	42.1
454	49.6	44.8	46.2	46.8
544	46.2	41.3	43.2	43.6

MIX CPR8

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	14.6	14.1	12.9	13.8
28	25.2	24.4	23.4	24.3
56	34.6	32.7	32.1	33.1
91	41.0	38.6	37.1	38.9
182	47.5	46.5	44.6	46.2
364	59.0	56.2	54.5	56.5
454	60.2	64.5	54.2	59.6
544	62.6	68.1	64.8	65.2

Elect. Tests 7. SR (Moist Cured) Testing Results (CPR9 to CPR17 Mixtures).

MIX CPR9

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	38.5	37.2	40.4	38.7
28	33.9	32.3	34.3	33.5
56	38.7	38.0	41.2	39.3
91	38.8	38.0	39.9	38.9
182	42.7	42.1	45.9	43.5
364	55.8	61.4	62.7	60.0
454	51.7	49.8	53.0	51.5
544	55.4	53.3	58.1	55.6

MIX CPR10

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	36.7	35.4	31.6	34.6
28	33.6	33.3	28.4	31.7
56	38.8	39.8	34.1	37.6
91	45.8	44.7	39.9	43.5
182	59.4	58.0	52.4	56.6
364	86.2	84.6	85.3	85.3
454	84.8	84.2	79.1	82.7
544	91.2	95.3	84.3	90.3

MIX CPR11

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	13.8	14.6	11.3	13.3
28	19.0	18.0	15.3	17.4
56	21.5	23.2	17.7	20.8
91	24.2	24.4	18.9	22.5
182	25.8	28.2	21.7	25.2
364	34.4	33.1	26.6	31.4
454	36.2	37.1	29.0	34.1
544	37.5	36.0	30.4	34.6

MIX CPR12

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	8.1	8.6	7.5	8.1
28	9.1	9.3	8.2	8.9
56	10.2	10.1	8.7	9.7
91	10.1	11.2	9.5	10.3
182	11.5	11.3	9.9	10.9
364	12.3	13.2	11.5	12.3
454	12.9	13.6	12.2	12.9
544	12.8	11.6	14.3	12.9

MIX CPR13

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	6.3	6.2	6.1	6.2
28	6.6	6.5	6.5	6.5
56	7.7	7.3	7.8	7.6
91	8.3	8.2	8.2	8.2
182	8.8	8.7	8.4	8.7
364	9.5	9.4	9.2	9.4
454	11.4	10.7	10.9	11.0
544	11.1	10.9	10.8	10.9

MIX CPR15

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	0.0	0.0	0.0	0.0
28	7.9	8.0	7.9	7.9
56	8.8	9.1	8.6	8.8
91	9.7	10.7	9.6	10.0
182	16.2	17.6	16.3	16.7
364	23.7	24.0	22.2	23.3
454	25.2	25.1	23.5	24.6
544	26.9	30.5	27.9	28.5

MIX CPR16

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	8.0	6.6	7.4	7.3
28	8.1	7.0	8.1	7.7
56	11.0	9.8	11.0	10.6
91	16.4	13.8	15.8	15.3
182	24.1	19.6	22.0	21.9
364	32.3	28.0	28.5	29.6
454	41.8	33.9	35.9	37.2
544	41.4	36.6	35.4	37.8

MIX CPR17

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	0.0	0.0	0.0	0.0
28	11.8	10.2	12.7	11.6
56	16.8	13.5	16.4	15.5
91	22.1	18.3	21.9	20.7
182	30.6	24.8	30.5	28.6
364	37.2	29.2	34.0	33.4
454	36.0	29.4	34.3	33.2
544	42.7	37.3	38.8	39.6

Elect. Tests 8. SR (Moist Cured) Testing Results (CPR18 to CPR21 Mixtures).

MIX CPR18

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	0.0	0.0	0.0	0.0
28	14.7	13.9	13.4	14.0
56	16.6	15.6	17.1	16.4
91	37.3	35.4	35.7	36.1
182	62.4	59.5	62.9	61.6
364	98.2	91.0	93.3	94.2
454	91.9	90.8	95.3	92.7
544	127.4	112.9	117.4	119.2

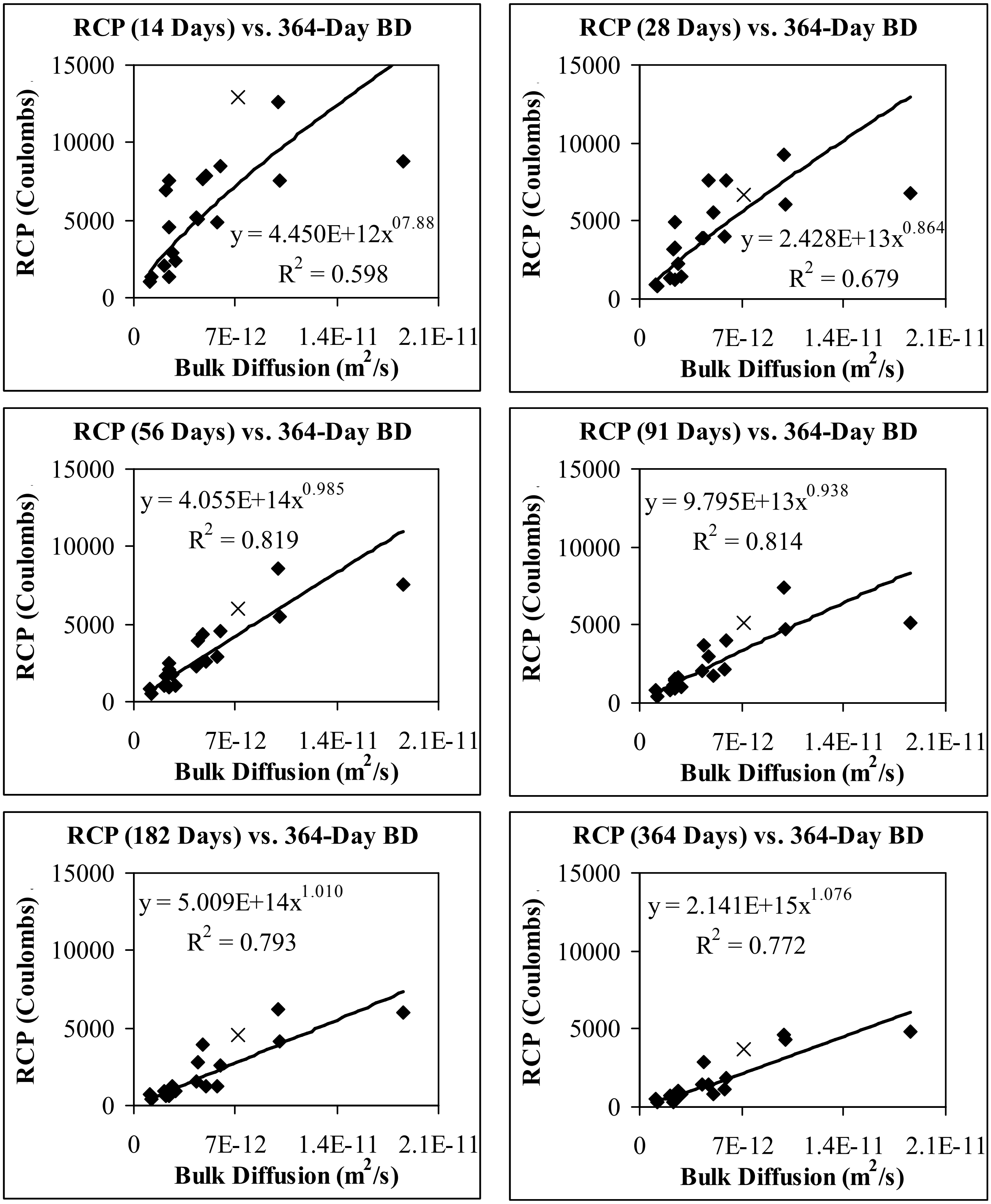
MIX CPR20

Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	0.0	0.0	0.0	0.0
28	13.2	13.0	13.2	13.1
56	13.9	14.1	16.7	14.9
91	23.1	23.2	22.0	22.8
182	31.6	33.4	33.3	32.7
364	39.6	42.8	44.0	42.1
454	40.2	39.7	40.8	40.2
544	48.0	51.5	50.3	49.9

MIX CPR21

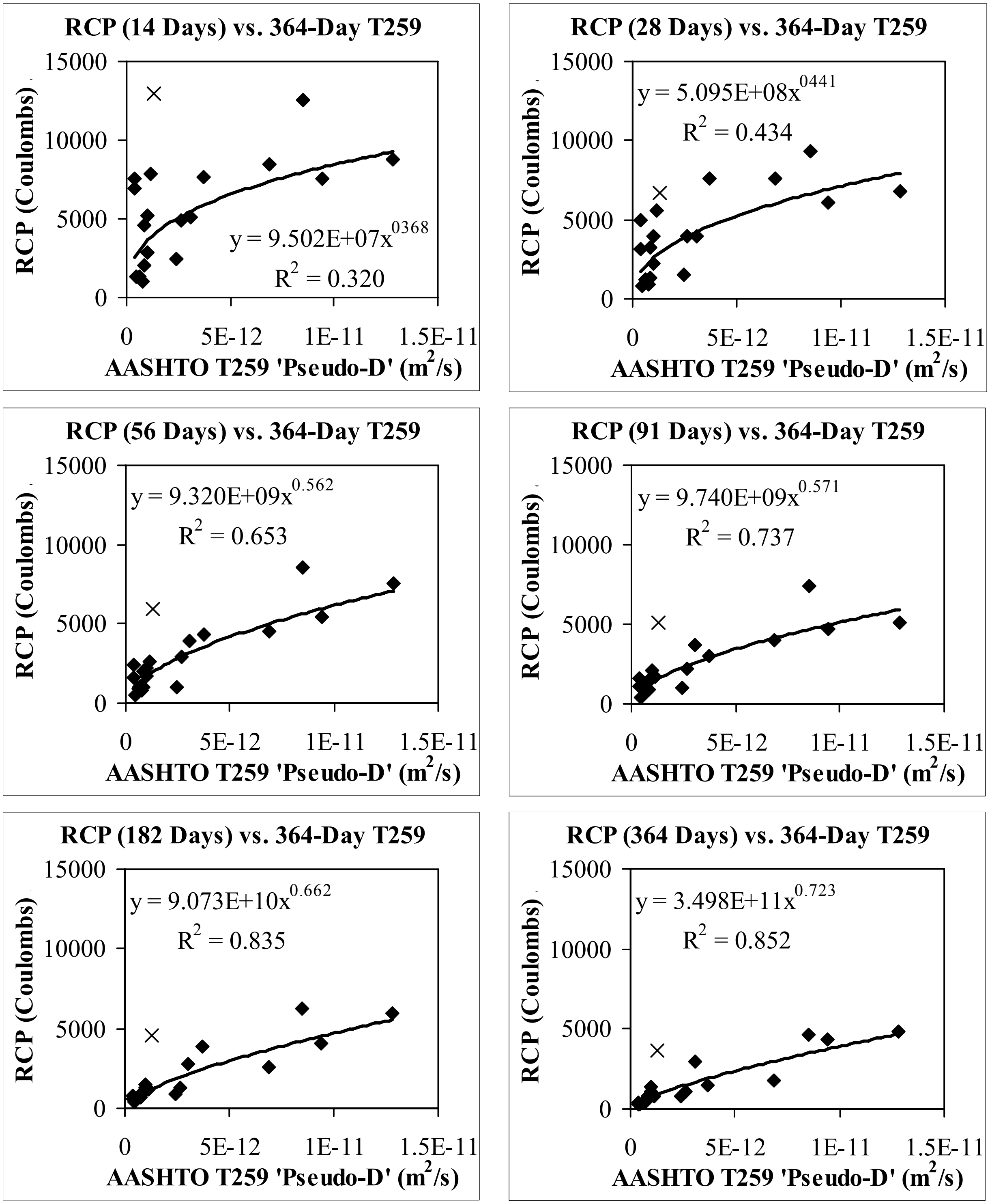
Testing Age	SR (Moist Cured) (kΩ.cm)			
(Days)	A	B	C	AVG.
14	0.0	0.0	0.0	0.0
28	14.0	11.9	12.8	12.9
56	16.4	15.4	17.0	16.3
91	21.7	19.2	19.2	20.0
182	42.4	41.9	42.0	42.1
364	72.1	65.9	61.0	66.4
454	73.1	72.4	65.7	70.4
544	92.3	87.1	80.5	86.6

Elect. Tests 9. RCP Coulombs vs. 364-Day Bulk Diffusion Coefficients.



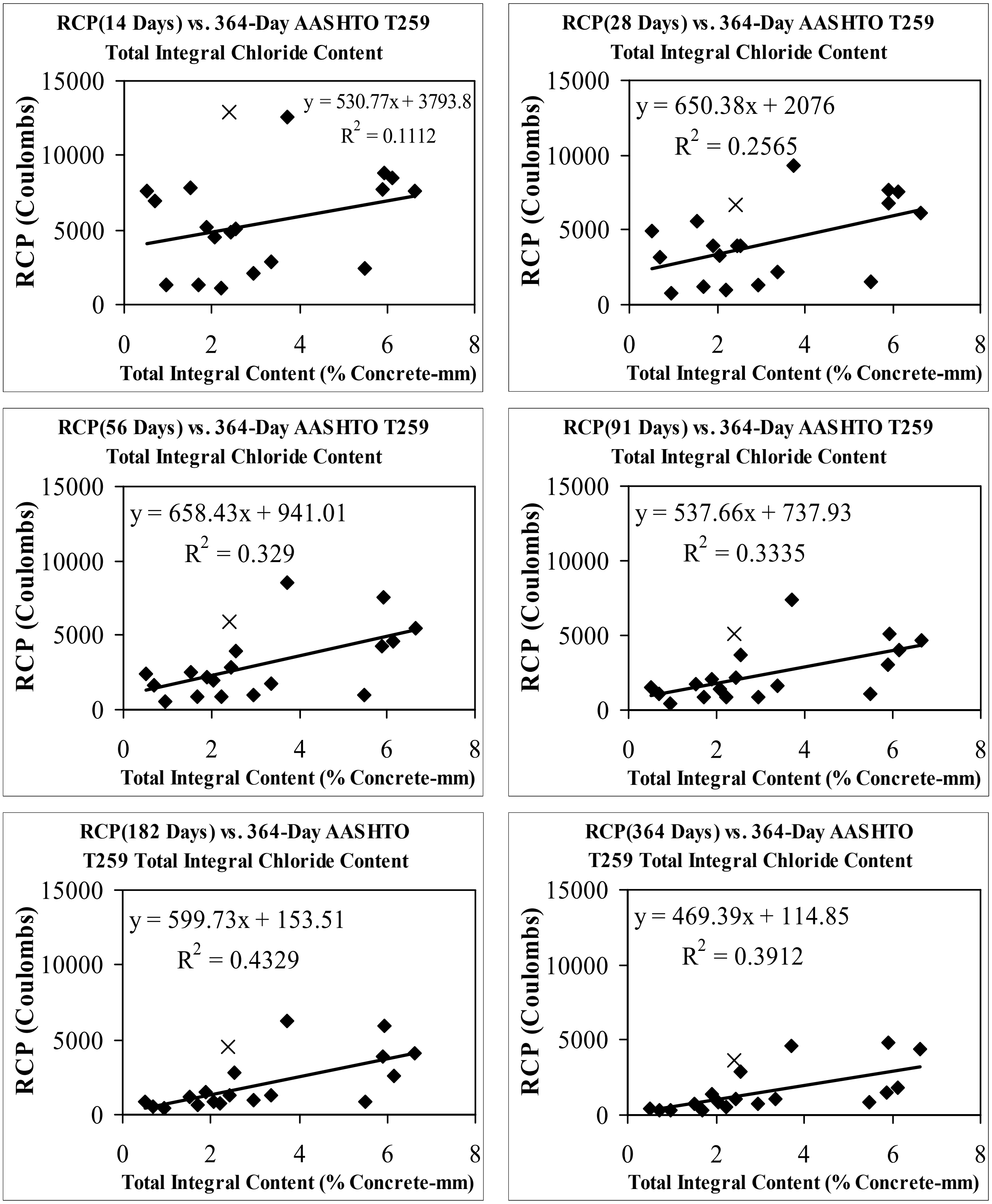
× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

Elect. Tests 10. RCP Coulombs vs. 364-Day AASHTO T259 Pseudo-Diffusion Coefficients.



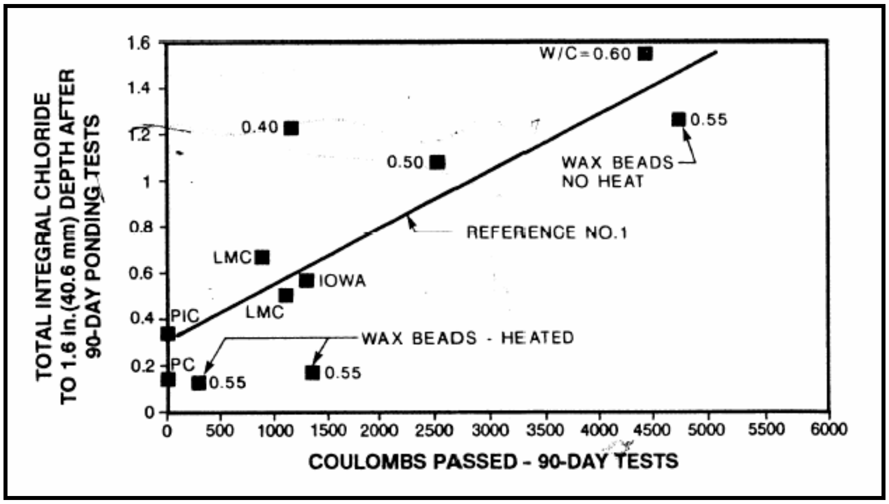
× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

Elect. Tests 11. RCP Coulombs vs. 364-Day T259 Total Integral Chloride Content.

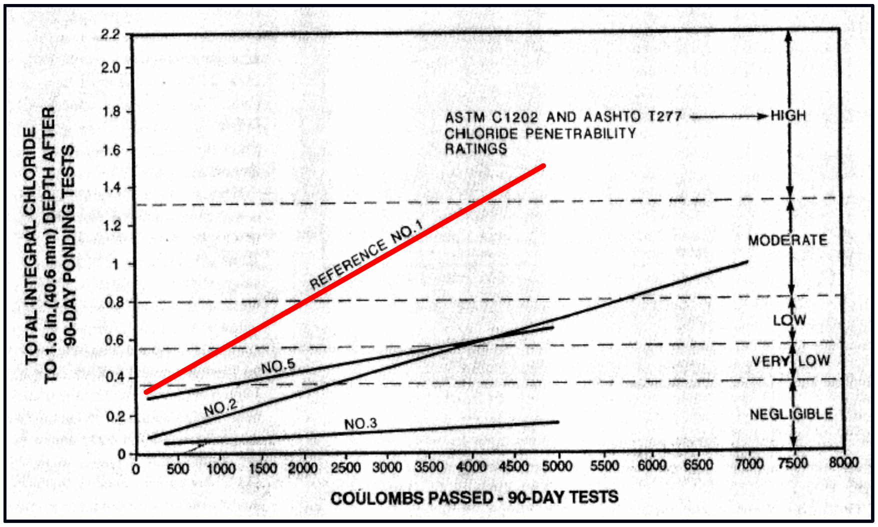


× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

Elect. Tests 12. RCP Standard Correlation Coulombs Limits Derivation (Whiting 1981).

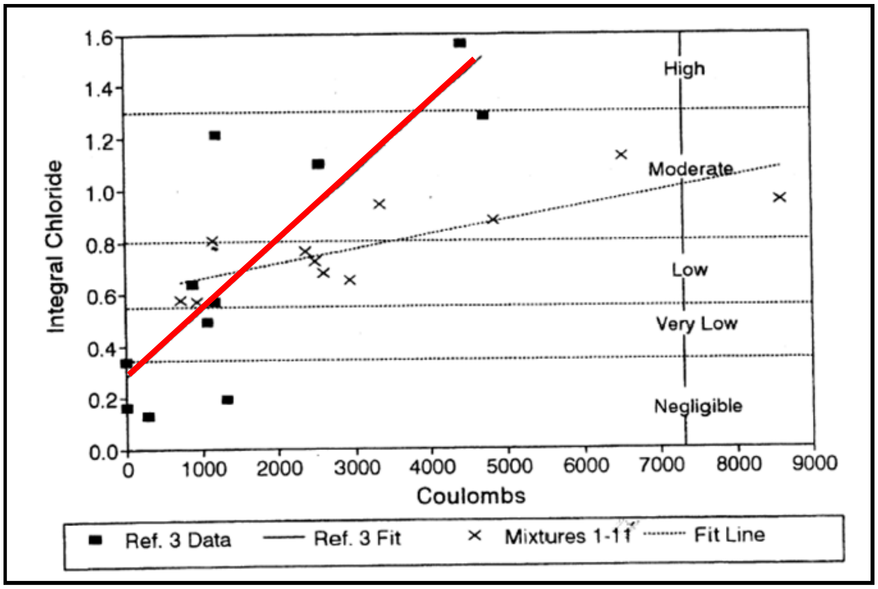


Elect. Tests 13. RCP Correlation Data from Several Reference Researches.



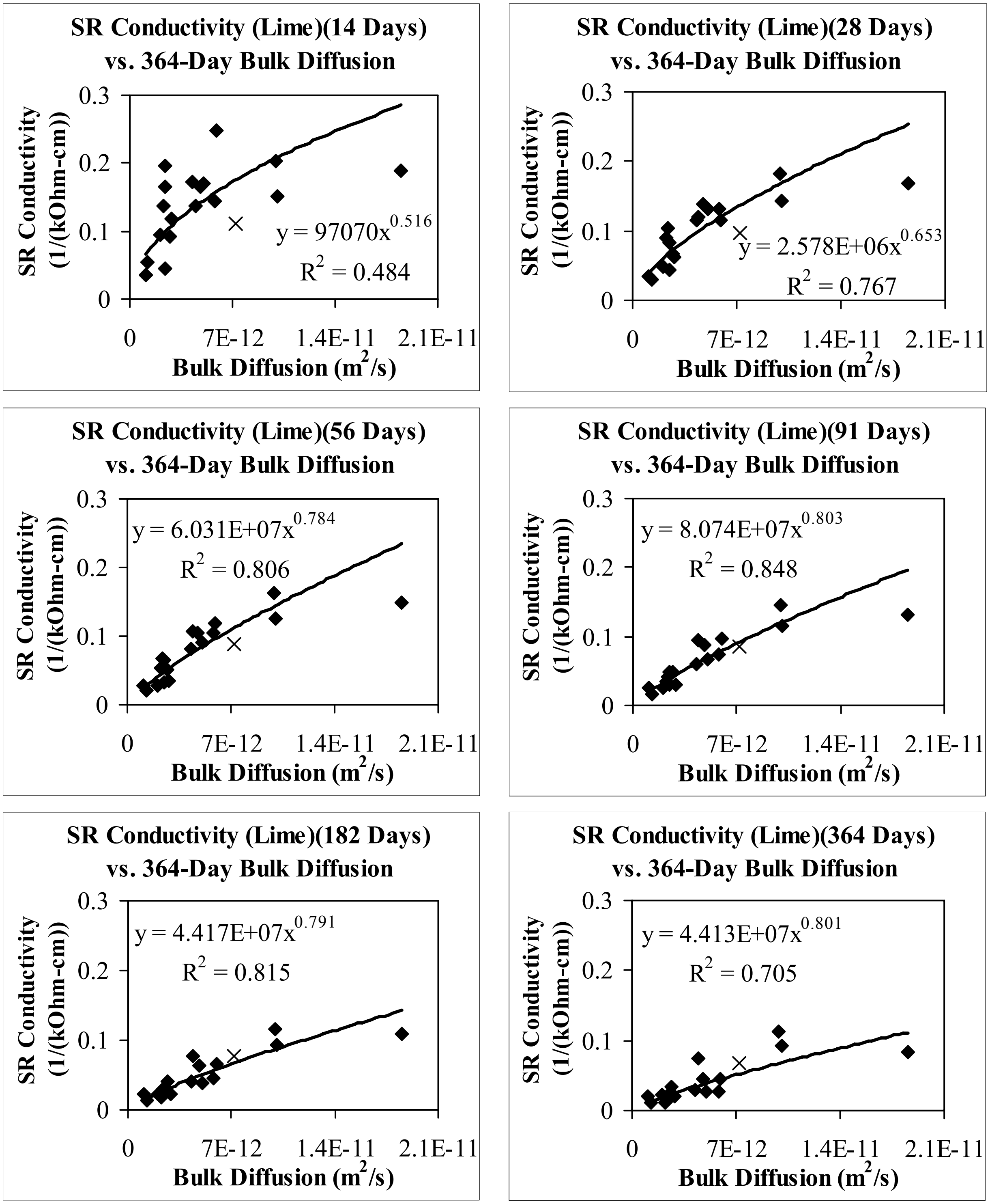
Reference No.1: Whiting, D. (1981) (RCP Test Method Correlation Data).
Reference No.2: Whiting, D. (1988).
Reference No.3: Whiting, D., and Dziedzic, W. (1989).
Reference No.5: Ozyildirim, C., and Halstead, W.J. (1988).

Elect. Tests 14. RCP Correlation Data from Several Reference Researches (Cont.)



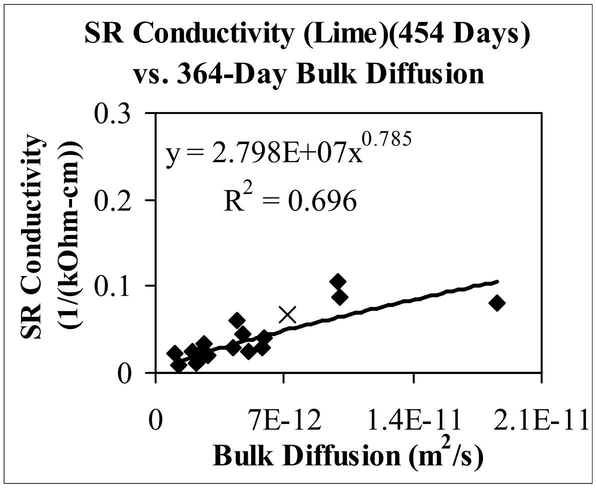
Reference No.3 Data: Whiting, D. (1981) (RCP Test Method correlation data).
Mixtures 1-11 Data: Scanlon, J.M. and Sherman, M.R. (1996).

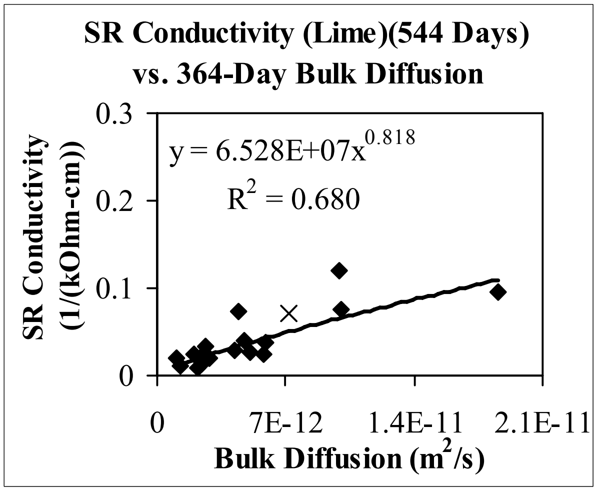
Elect. Tests 15. SR (Lime Cured) vs. 364-Day Bulk Diffusion Coefficients.



× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

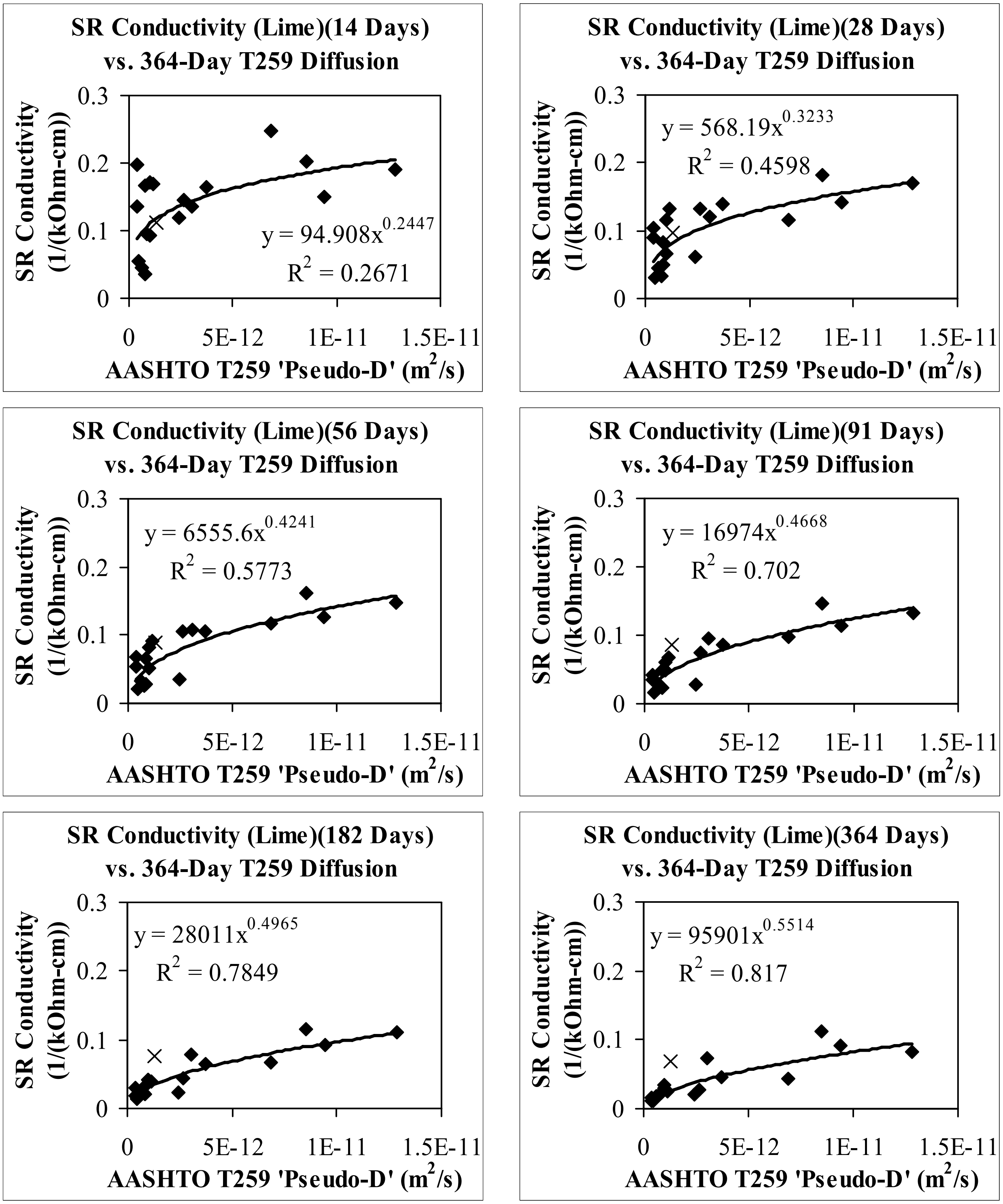
Elect. Tests 16. SR (Lime Cured) vs. 364-Day Bulk Diffusion Coefficients (Cont.).





× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

Elect. Tests 17. SR (Lime Cured) vs. 364-Day AASHTO T259 Pseudo-Diffusion Coefficients.



SR Conductivity (Lime)(14 Days) vs. 364-Day T259 Diffusion

SR Conductivity (Lime)(28 Days) vs. 364-Day T259 Diffusion

SR Conductivity (Lime)(56 Days) vs. 364-Day T259 Diffusion

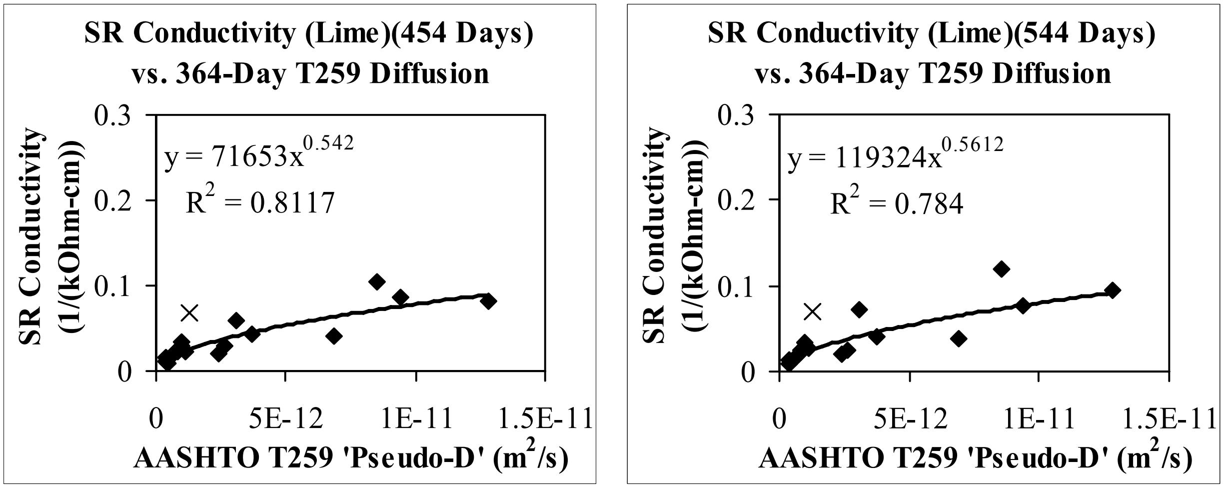
SR Conductivity (Lime)(91 Days) vs. 364-Day T259 Diffusion

SR Conductivity (Lime)(182 Days) vs. 364-Day T259 Diffusion

SR Conductivity (Lime)(364 Days) vs. 364-Day T259 Diffusion

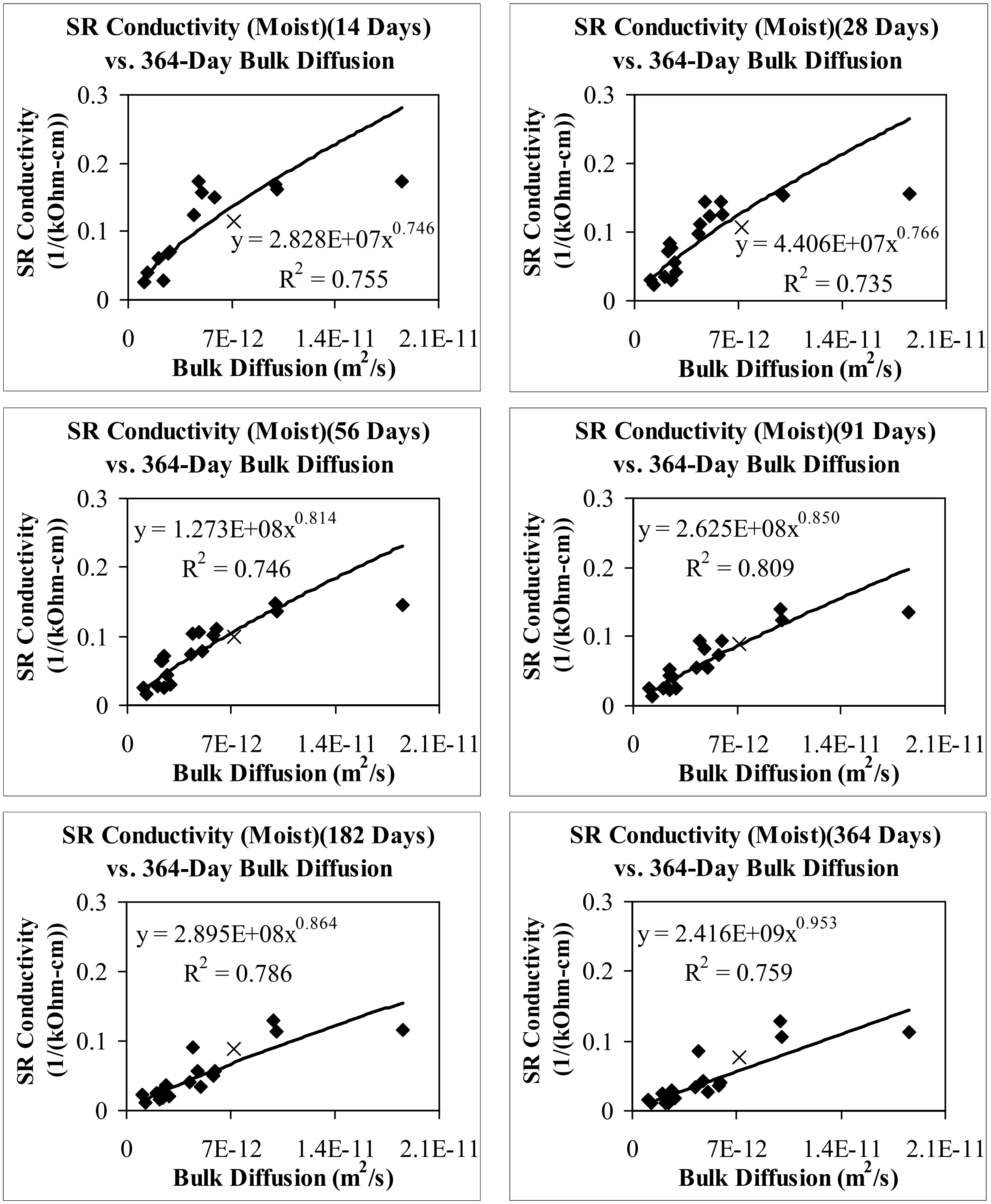
× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

Elect. Tests 18. SR (Lime Cured) vs. 364-Day AASHTO T259 Pseudo-Diffusion Coefficients (Cont.).



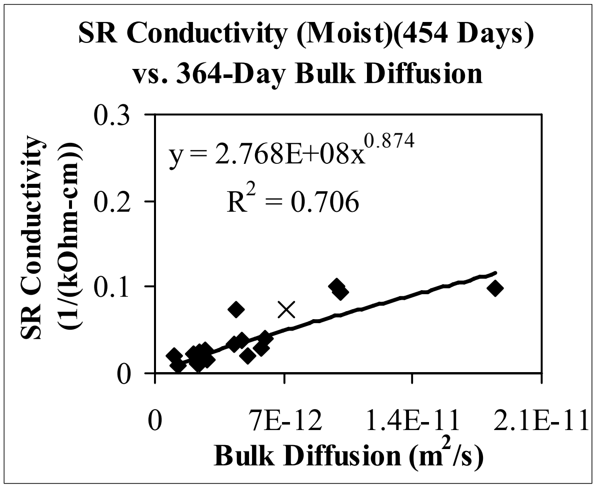
× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

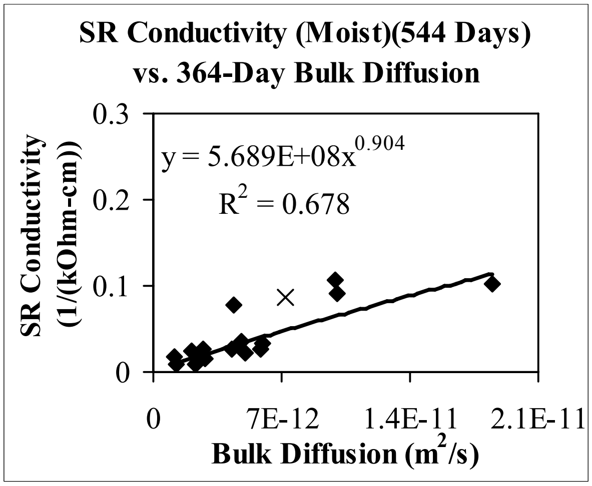
Elect. Tests 19. SR (Moist Cured) vs. 364-Day Bulk Diffusion Coefficients.



× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

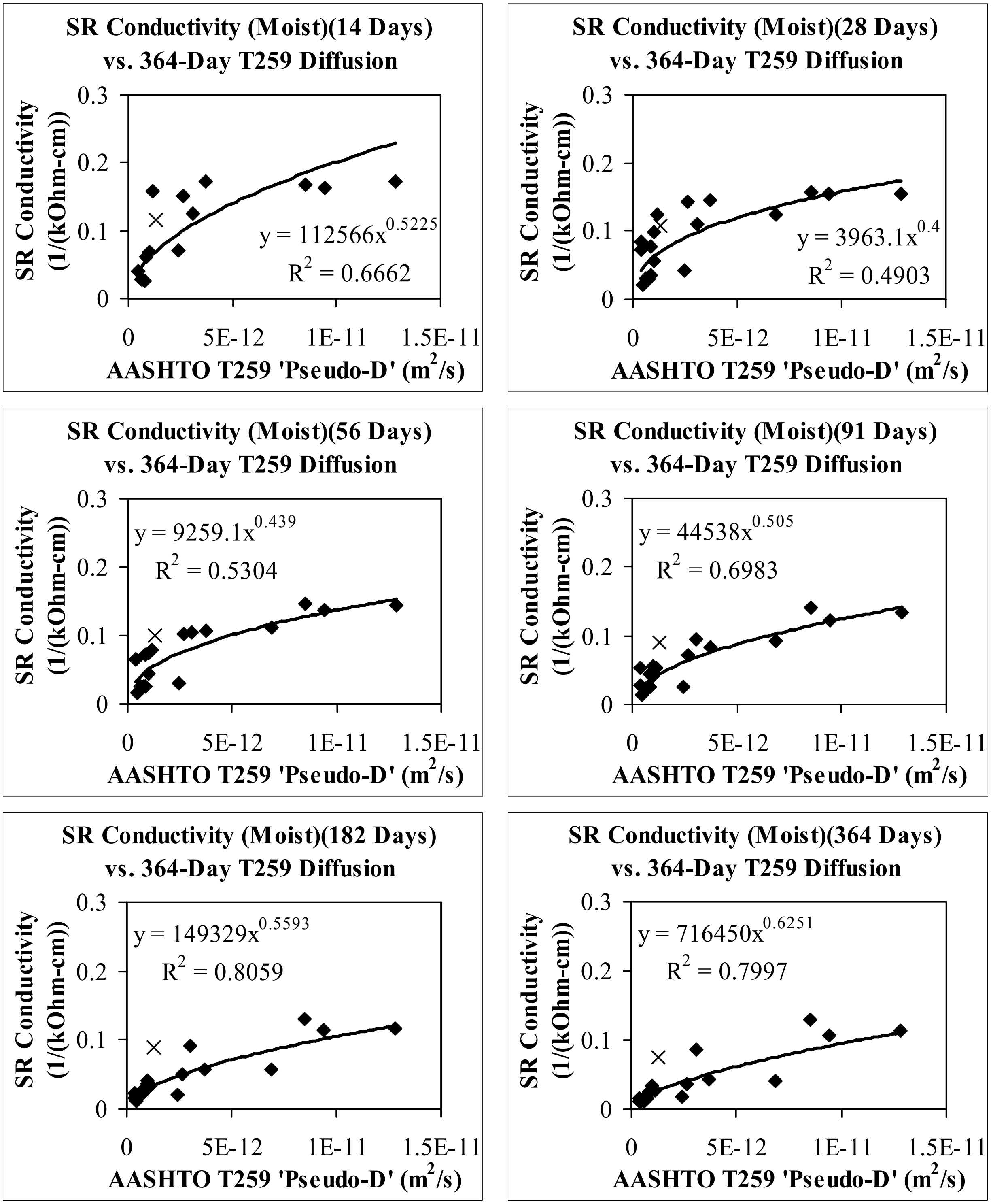
Elect. Tests 20. SR (Lime Cured) vs. 364-Day Bulk Diffusion Coefficients (Cont.).





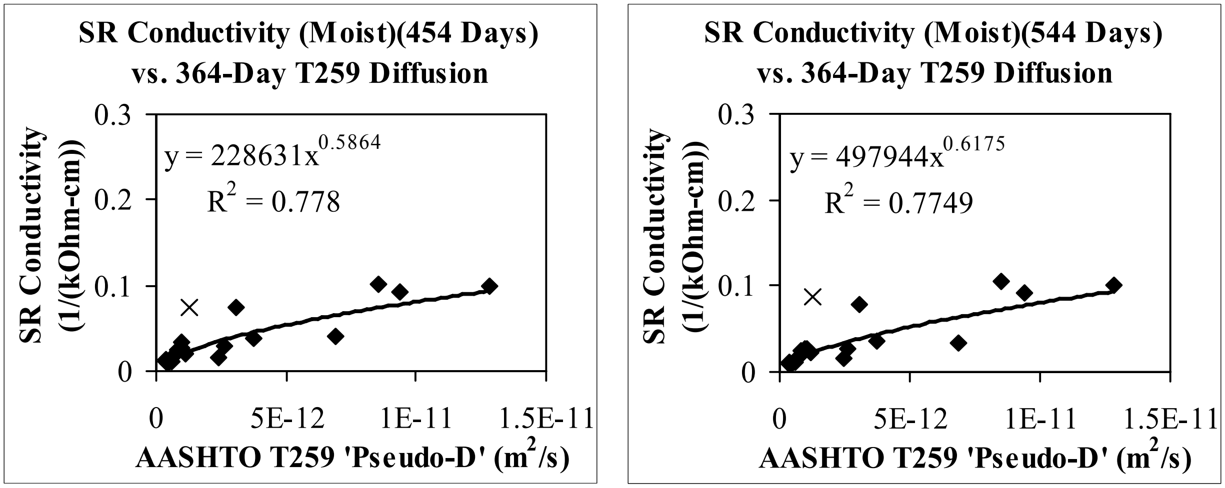
× Concrete mixture containing Calcium Nitrate (CPR12 It was not include in the general correlation calculations.

Elect. Tests 21. SR (Moist Cured) vs. 364-Day AASHTO T259 Pseudo-Diffusion Coefficients.



× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

Elect. Tests 22. SR (Moist Cured) vs. 364-Day AASHTO T259 Pseudo-Diffusion Coefficients (Cont.).



× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

Elect. Tests 23. Impressed Current Testing Results (CPR1 to CPR12 Mixtures).

MIX CPR1

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	8	494
B	9	471
C	9	163(*)
AVG	**9**	**483**

MIX CPR2

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	29	934
B	36	914
C	26	896
AVG	**30**	**915**

MIX CPR3

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	11	547
B	16	564
C	16	629
AVG	**14**	**580**

MIX CPR4

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	96	5043
B	114	5084
C	116	4799
AVG	**109**	**4975**

MIX CPR5

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	31	1486
B	28	1461
C	46	1619
AVG	**35**	**1522**

MIX CPR6

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	18	780
B	22	830
C	21	761
AVG	**20**	**790**

MIX CPR7

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	61	2542
B	61	2605
C	61	2750
AVG	**61**	**2632**

MIX CPR8

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	62	3204
B	N/A	N/A
C	60	3229
AVG	**61**	**3217**

MIX CPR9

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	60	3216
B	54	2884
C	50	3341
AVG	**55**	**3147**

MIX CPR10

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	52	4809
B	48	4034
C	54	3727
AVG	**51**	**4190**

MIX CPR11

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	41	1735
B	N/A	N/A
C	45	1860
AVG	**43**	**1798**

MIX CPR12

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	34	880
B	N/A	N/A
C	35	789
AVG	**35**	**835**

Elect. Tests 24. Impressed Current Testing Results (CPR13 to CPR21).

MIX CPR13

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	20	638
B	15	617
C	21	689
AVG	**19**	**648**

MIX CPR15

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	8	541
B	5	481
C	4	493
AVG	**6**	**505**

MIX CPR16

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	11	764
B	9	871
C	9	637
AVG	**10**	**757**

MIX CPR17

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	31	1027
B	42	1232
C	35	1138
AVG	**36**	**1132**

MIX CPR18

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	72	1686
B	79	1734
C	86	1994
AVG	**79**	**1805**

MIX CPR20

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A	21	690
B(*)	6(*)	774(*)
C	24	1143
AVG	**22.5**	**916.5**

MIX CPR21

SAMPLE	**FAILURE (Days)**	**RESISTANCE (Ω)**
A(*)	20(*)	955(*)
B	50	1238
C	50	1299
AVG	**50**	**1269**

(*) Result discarded for mean value calculations.

Elect. Tests 25. RMT Silver Nitrate Penetration (CPR1 to CPR10 Mixtures).

MIX CPR1

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	**A**	**B**	**C**	**AVG.**
14	-	-	-	-
28	-	-	-	-
56	-	-	-	-
91	-	-	-	-
182	1.337	1.588	1.581	1.502
364	1.386	1.273	1.103	1.254

MIX CPR2

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	**A**	**B**	**C**	**AVG.**
14	-	-	-	-
28	-	-	-	-
56	-	-	-	-
91	-	-	-	-
182	0.473	0.459	0.508	0.480
367	0.667	0.438	0.569	0.558

MIX CPR3

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	**A**	**B**	**C**	**AVG.**
14	-	-	-	-
28	-	-	-	-
56	-	-	-	-
91	0.444	0.446	0.454	0.448
182	0.366	0.344	0.323	0.344
364	0.950	1.195	1.043	1.063

MIX CPR4

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	**A**	**B**	**C**	**AVG.**
14	-	-	-	-
28	-	-	-	-
56	-	-	-	-
91	0.316	0.098	0.136	0.183
182	0.380	0.409	0.249	0.346
364	0.307	0.135	0.223	0.222

MIX CPR5

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	**A**	**B**	**C**	**AVG.**
14	-	-	-	-
28	-	-	-	-
56	-	-	-	-
91	0.676	0.791	0.808	0.758
182	0.493	0.525	0.445	0.487
364	0.311	0.218	0.457	0.329

MIX CPR6

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	**A**	**B**	**C**	**AVG.**
14	0.645	0.526	0.638	0.603
28	0.528	0.509	0.545	0.527
56	1.143	0.812	0.877	0.944
91	0.587	0.714	0.785	0.695
182	0.810	1.205	0.714	0.910
364	0.806	0.691	1.142	0.879

MIX CPR7

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	**A**	**B**	**C**	**AVG.**
14	0.461	0.844	0.802	0.702
28	0.329	0.282	0.383	0.332
56	0.347	0.283	0.473	0.368
91	0.606	0.515	0.600	0.574
182	0.431	0.521	0.367	0.439
364	0.435	0.419	0.380	0.411

MIX CPR8

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	**A**	**B**	**C**	**AVG.**
14	0.787	0.826	0.549	0.720
28	0.739	0.547	0.724	0.670
56	0.680	0.478	0.545	0.568
91	0.732	0.553	0.642	0.642
182	0.456	0.182	0.484	0.374
364	0.379	0.559	0.433	0.457

MIX CPR9

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	**A**	**B**	**C**	**AVG.**
14	0.486	0.432	0.605	0.508
28	0.479	0.335	0.513	0.442
56	0.485	0.374	0.288	0.382
91	0.293	0.323	0.395	0.337
182	0.319	0.469	0.420	0.403
364	0.333	0.368	0.285	0.329

MIX CPR10

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	**A**	**B**	**C**	**AVG.**
14	0.898	1.055	0.907	0.953
28	0.393	0.503	0.565	0.487
56	0.559	0.560	0.435	0.518
91	0.674	0.495	0.318	0.495
182	0.514	0.464	0.413	0.464
364	0.182	0.284	0.319	0.262

Elect. Tests 26. RMT Silver Nitrate Penetration (CPR11 to CPR21 Mixtures).

MIX CPR11

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	A	B	C	AVG.
14	0.692	0.421	0.368	0.494
28	0.424	0.464	0.525	0.471
56	0.691	0.496	0.528	0.572
91	0.404	0.452	0.331	0.396
182	0.773	0.501	0.731	0.668
364	0.574	0.360	0.441	0.459

MIX CPR12

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	A	B	C	AVG.
14	0.299	0.426	0.394	0.373
28	0.991	0.942	0.863	0.932
56	0.354	0.248	0.384	0.329
91	0.676	0.647	0.606	0.643
182	0.744	0.778	0.672	0.731
364	0.639	0.600	0.579	0.606

MIX CPR13

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	A	B	C	AVG.
14	-	-	-	-
28	-	-	-	-
56	-	-	-	-
91	-	-	-	-
182	1.124	1.209	1.322	1.219
364	1.088	1.184	1.172	1.148

MIX CPR15

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	A	B	C	AVG.
14	-	-	-	-
28	-	-	-	-
56	-	-	-	-
91	-	-	-	-
182	-	-	-	-
364	0.906	0.965	1.124	0.999

MIX CPR16

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	A	B	C	AVG.
14	-	-	-	-
28	-	-	-	-
56	-	-	-	-
91	-	-	-	-
182	0.572	0.565	0.520	0.552
364	0.694	0.992	0.506	0.731

MIX CPR17

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	A	B	C	AVG.
14	-	-	-	-
28	-	-	-	-
56	-	-	-	-
91	-	-	-	-
182	0.572	0.565	0.520	0.552
364	0.563	0.597	0.590	0.583

MIX CPR18

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	A	B	C	AVG.
14	-	-	-	-
28	-	-	-	-
56	-	-	-	-
91	-	-	-	-
182	0.912	0.786	0.000	0.566
364	0.198	0.204	0.316	0.239

MIX CPR20

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	A	B	C	AVG.
14	-	-	-	-
28	-	-	-	-
56	-	-	-	-
91	-	-	-	-
182	0.306	0.444	0.496	0.415
364	0.252	0.590	0.668	0.503

MIX CPR21

Testing Age	AgNO$_3$ Ave. Penetration (in)			
(Days)	A	B	C	AVG.
14	-	-	-	-
28	-	-	-	-
56	-	-	-	-
91	-	-	-	-
182	-	-	-	-
364	0.139	0.237	0.201	0.192

Elect. Tests 27. RMT Chloride Profile Testing Results (CPR1 to CPR4 Mixtures).

MIX CPR1

Concrete Unit W. 140.62 pcf

Binder Unit W. 564.00 lb/yd^3

Test	Depth	NaCl (lb/yd^3)				%NaCl	
(Day)	(in)	A	B	C	AVG	(Conc.)	(Binder)
14	0.375	6.01	6.18	5.18	5.79	0.152	1.026
	0.625	1.87	0.87	1.35	1.36	0.036	0.241
	0.875	0.69	0.30	0.72	0.57	0.015	0.101
28	0.375	4.51	2.73	4.90	4.04	0.107	0.717
	0.625	0.88	0.64	0.92	0.82	0.021	0.145
	0.875	0.12	0.35	0.22	0.23	0.006	0.040
56	0.375	16.06	13.96	13.57	14.53	0.383	2.576
	0.625	11.18	10.75	10.71	10.88	0.286	1.928
	0.875	9.21	7.98	8.05	8.41	0.222	1.491
91	0.375	12.03	14.48	12.71	13.08	0.344	2.318
	0.625	11.53	10.43	11.36	11.10	0.292	1.969
	0.875	7.78	9.24	7.84	8.28	0.218	1.469
182	0.375	0.00	0.00	0.00	0.00	0.000	0.000
	0.625	0.00	0.00	0.00	0.00	0.000	0.000
	0.875	0.00	0.00	0.00	0.00	0.000	0.000
364	0.375	12.92	15.69	17.43	15.34	0.404	2.721
	0.625	10.38	11.62	12.95	11.65	0.307	2.066
	0.875	6.62	6.97	8.26	7.28	0.192	1.291

MIX CPR2 ▨ Sample not included in Average

Concrete Unit W. 144.62 pcf

Binder Unit W. 752.00 lb/yd^3

Test	Depth	NaCl (lb/yd^3)				%NaCl	
(Day)	(in)	A	B	C	AVG	(Conc.)	(Binder)
14	0.375	13.80	13.53	15.47	14.27	0.365	1.897
	0.625	6.51	8.51	7.98	7.67	0.196	1.020
	0.875	2.31	3.88	2.88	3.02	0.077	0.402
28	0.375	0.00	12.32	1.43	12.32	0.316	1.639
	0.625	0.00	7.15	7.11	7.13	0.183	0.948
	0.875	0.00	2.54	2.15	2.34	0.060	0.312
56	0.375	8.62	10.68	8.82	9.37	0.240	1.246
	0.625	3.48	4.72	4.12	4.11	0.105	0.546
	0.875	2.25	1.91	1.91	2.03	0.052	0.269
91	0.375	10.65	15.63	10.97	12.41	0.318	1.651
	0.625	5.65	8.74	4.28	6.22	0.159	0.828
	0.875	2.85	2.31	2.16	2.44	0.063	0.325
182	0.375	10.41	7.32	13.10	10.28	0.263	1.367
	0.625	2.43	4.24	3.66	3.44	0.088	0.457
	0.875	0.84	2.35	1.81	1.67	0.043	0.222
367	0.375	8.39	9.01	10.08	9.16	0.234	1.217
	0.625	4.67	2.67	4.50	3.95	0.101	0.525
	0.875	2.16	1.09	2.15	1.80	0.046	0.239

MIX CPR3

Concrete Unit W. 140.40 pcf

Binder Unit W. 752.00 lb/yd^3

Test	Depth	NaCl (lb/yd^3)				%NaCl	
(Day)	(in)	A	B	C	AVG	(Conc.)	(Binder)
14	0.375	5.58	6.15	5.68	5.80	0.153	0.772
	0.625	1.41	1.30	2.07	1.59	0.042	0.212
	0.875	0.50	0.33	0.54	0.46	0.012	0.061
28	0.375	11.14	6.11	8.45	8.57	0.226	1.139
	0.625	1.84	0.86	1.75	1.49	0.039	0.198
	0.875	0.60	0.58	1.07	0.75	0.020	0.100
56	0.375	5.61	5.13	5.96	5.57	0.147	0.740
	0.625	1.98	1.70	1.64	1.77	0.047	0.236
	0.875	0.54	0.82	0.37	0.58	0.015	0.077
91	0.375	5.08	4.58	5.38	5.01	0.132	0.666
	0.625	0.57	1.38	1.28	1.08	0.028	0.143
	0.875	0.35	0.41	0.50	0.42	0.011	0.056
182	0.375	5.68	4.45	4.75	4.96	0.131	0.660
	0.625	1.08	2.91	1.21	1.73	0.046	0.230
	0.875	0.46	1.40	0.64	0.83	0.022	0.111
364	0.375	19.14	14.84	14.51	16.16	0.426	2.149
	0.625	12.82	10.96	11.70	11.83	0.312	1.572
	0.875	6.20	6.82	6.16	6.39	0.169	0.850

MIX CPR4 ▨ Sample not included in Average

Concrete Unit W. 142.32 pcf

Binder Unit W. 900.00 lb/yd^3

Test	Depth	NaCl (lb/yd^3)				%NaCl	
(Day)	(in)	A	B	C	AVG	(Conc.)	(Binder)
14	0.375	11.14	8.22	8.48	9.28	0.245	1.234
	0.625	4.39	5.17	3.54	4.37	0.115	0.580
	0.875	1.50	1.49	1.32	1.44	0.038	0.191
28	0.375	4.43	7.21	6.42	6.02	0.159	0.800
	0.625	2.81	3.80	3.83	3.48	0.092	0.463
	0.875	1.56	13.03	1.08	1.32	0.035	0.176
56	0.375	4.33	2.02	2.56	2.97	0.078	0.395
	0.625	1.97	1.34	1.88	1.73	0.046	0.230
	0.875	1.19	0.59	0.90	0.89	0.023	0.118
91	0.375	0.00	0.00	0.00	0.00	0.000	0.000
	0.625	0.00	0.00	0.00	0.00	0.000	0.000
	0.875	0.00	0.00	0.00	0.00	0.000	0.000
182	0.375	0.00	0.00	0.00	0.00	0.000	0.000
	0.625	0.00	0.00	0.00	0.00	0.000	0.000
	0.875	0.00	0.00	0.00	0.00	0.000	0.000
364	0.375	0.00	0.00	0.00	0.00	0.000	0.000
	0.625	0.00	0.00	0.00	0.00	0.000	0.000
	0.875	0.00	0.00	0.00	0.00	0.000	0.000

Elect. Tests 28. RMT Chloride Profile Testing Results (CPR5 to CPR8 Mixtures).

MIX CPR5

Concrete Unit W. 144.32 pcf

Binder Unit W. 752.00 lb/yd^3

Test	**Depth**	**NaCl (lb/yd^3)**				**%NaCl**	
(Day)	**(in)**	**A**	**B**	**C**	**AVG**	**(Conc.)**	**(Binder)**
14	0.375	4.81	4.62	4.69	4.71	0.121	0.626
	0.625	0.00	1.53	1.17	1.35	0.035	0.180
	0.875	0.00	0.66	0.27	0.46	0.012	0.062
28	0.375	14.30	12.91	13.24	13.48	0.346	1.793
	0.625	10.30	7.86	8.25	8.80	0.226	1.171
	0.875	6.81	8.33	6.00	7.04	0.181	0.937
56	0.375	16.19	14.85	14.96	15.33	0.393	2.039
	0.625	10.57	12.32	12.94	11.94	0.306	1.588
	0.875	7.55	8.47	9.41	8.48	0.218	1.127
91	0.375	12.62	11.71	10.27	11.54	0.296	1.534
	0.625	6.57	8.90	7.30	7.59	0.195	1.009
	0.875	5.97	5.86	4.21	5.35	0.137	0.711
182	0.375	10.14	9.50	8.60	9.41	0.242	1.251
	0.625	5.99	5.06	5.06	5.37	0.138	0.714
	0.875	2.67	2.92	3.66	3.08	0.079	0.409
364	0.375	6.25	4.46	4.70	5.14	0.132	0.684
	0.625	1.76	1.41	2.81	2.00	0.051	0.265
	0.875	1.46	0.86	1.55	1.29	0.033	0.172

MIX CPR6

Concrete Unit W. 140.52 pcf

Binder Unit W. 752.00 lb/yd^3

Test	**Depth**	**NaCl (lb/yd^3)**				**%NaCl**	
(Day)	**(in)**	**A**	**B**	**C**	**AVG**	**(Conc.)**	**(Binder)**
14	0.375	5.91	7.13	5.91	6.31	0.166	0.840
	0.625	3.10	0.00	1.50	2.30	0.061	0.305
	0.875	0.74	0.00	0.42	0.58	0.015	0.078
28	0.375	6.97	5.22	6.06	6.08	0.160	0.809
	0.625	1.34	0.89	1.83	1.35	0.036	0.180
	0.875	0.73	0.55	0.43	0.57	0.015	0.076
56	0.375	18.79	14.62	17.54	16.98	0.448	2.258
	0.625	11.25	7.73	13.71	10.90	0.287	1.449
	0.875	6.17	3.63	8.54	6.11	0.161	0.813
91	0.375	11.36	11.56	12.32	11.75	0.310	1.562
	0.625	5.67	7.96	6.45	6.69	0.176	0.890
	0.875	1.97	3.56	2.36	2.63	0.069	0.350
182	0.375	13.86	15.74	14.97	14.86	0.392	1.976
	0.625	7.96	13.46	11.36	10.93	0.288	1.453
	0.875	3.84	7.04	7.61	6.16	0.162	0.820
364	0.375	14.47	15.58	10.82	13.63	0.359	1.812
	0.625	8.39	8.63	8.40	8.47	0.223	1.126
	0.875	4.14	5.21	4.49	4.61	0.122	0.613

MIX CPR7

Concrete Unit W. 143.72 pcf

Binder Unit W. 752.00 lb/yd^3

Test	**Depth**	**NaCl (lb/yd^3)**				**%NaCl**	
(Day)	**(in)**	**A**	**B**	**C**	**AVG**	**(Conc.)**	**(Binder)**
14	0.375	18.69	18.04	21.30	19.34	0.498	2.572
	0.625	8.64	17.15	17.05	14.28	0.368	1.899
	0.875	5.55	9.79	8.81	8.05	0.207	1.070
28	0.375	11.67	10.23	9.77	10.56	0.272	1.404
	0.625	5.76	6.08	3.55	5.13	0.132	0.682
	0.875	3.38	3.45	2.92	3.25	0.084	0.432
56	0.375	6.31	7.51	8.67	7.49	0.193	0.996
	0.625	2.23	3.46	4.81	3.50	0.090	0.466
	0.875	1.36	2.05	3.72	2.38	0.061	0.316
91	0.375	6.64	8.19	6.50	7.11	0.183	0.946
	0.625	5.13	3.69	4.49	4.44	0.114	0.590
	0.875	2.03	1.61	2.25	1.96	0.051	0.261
182	0.375	5.34	8.13	7.37	6.95	0.179	0.924
	0.625	3.00	2.94	2.87	2.94	0.076	0.390
	0.875	1.10	3.53	1.07	1.90	0.049	0.253
364	0.375	5.82	5.03	4.53	5.13	0.132	0.682
	0.625	1.19	3.57	3.57	2.78	0.072	0.369
	0.875	0.47	1.60	1.24	1.10	0.028	0.147

MIX CPR8

Concrete Unit W. 139.72 pcf

Binder Unit W. 752.00 lb/yd^3

Test	**Depth**	**NaCl (lb/yd^3)**				**%NaCl**	
(Day)	**(in)**	**A**	**B**	**C**	**AVG**	**(Conc.)**	**(Binder)**
14	0.375	10.54	11.72	13.98	12.08	0.320	1.606
	0.625	4.63	5.74	6.78	5.71	0.151	0.760
	0.875	2.21	2.43	2.33	2.32	0.062	0.309
28	0.375	11.71	11.44	12.56	11.90	0.316	1.583
	0.625	6.27	5.45	7.47	6.40	0.170	0.851
	0.875	3.72	3.63	4.34	3.90	0.103	0.519
56	0.375	8.05	9.90	7.88	8.61	0.228	1.145
	0.625	5.92	5.96	3.94	5.27	0.140	0.701
	0.875	3.96	2.97	1.36	2.76	0.073	0.367
91	0.375	12.30	9.55	9.20	10.35	0.274	1.376
	0.625	6.78	6.43	3.67	5.63	0.149	0.748
	0.875	2.62	3.45	2.18	2.75	0.073	0.366
182	0.375	8.11	7.40	7.84	7.78	0.206	1.035
	0.625	3.38	3.91	3.48	3.59	0.095	0.477
	0.875	2.98	1.87	2.11	2.32	0.061	0.308
364	0.375	6.40	7.92	6.71	7.01	0.186	0.932
	0.625	1.94	2.65	1.73	2.11	0.056	0.280
	0.875	1.40	1.36	0.98	1.25	0.033	0.166

Elect. Tests 29. RMT Chloride Profile Testing Results (CPR9 to CPR10 Mixtures).

MIX CPR9
Concrete Unit W. 145.22 pcf
Binder Unit W. 752.00 lb/yd^3

Test	Depth	NaCl (lb/yd^3)				%NaCl	
(Day)	(in)	A	B	C	AVG	(Conc.)	(Binder)
14	0.375	8.74	7.58	7.36	7.89	0.201	1.050
	0.625	2.51	3.75	5.06	3.77	0.096	0.501
	0.875	0.93	2.05	2.07	1.68	0.043	0.224
28	0.375	7.26	8.13	8.37	7.92	0.202	1.053
	0.625	3.16	4.75	2.71	3.54	0.090	0.471
	0.875	2.44	1.47	1.03	1.64	0.042	0.219
56	0.375	6.99	6.91	7.51	7.14	0.182	0.949
	0.625	3.70	1.57	4.71	3.33	0.085	0.442
	0.875	2.78	1.03	2.46	2.09	0.053	0.278
91	0.375	8.28	5.54	6.71	6.84	0.175	0.910
	0.625	3.63	3.07	1.96	2.89	0.074	0.384
	0.875	1.59	1.65	1.28	1.50	0.038	0.200
182	0.375	6.24	4.14	4.44	4.94	0.126	0.657
	0.625	2.47	1.95	1.94	2.12	0.054	0.282
	0.875	1.24	1.21	1.60	1.35	0.034	0.179
364	0.375	5.34	5.37	5.55	5.42	0.138	0.721
	0.625	1.18	1.22	1.75	1.39	0.035	0.184
	0.875	1.16	1.15	0.76	1.02	0.026	0.136

MIX CPR10
Concrete Unit W. 144.02 pcf
Binder Unit W. 752.00 lb/yd^3

Test	Depth	NaCl (lb/yd^3)				%NaCl	
(Day)	(in)	A	B	C	AVG	(Conc.)	(Binder)
14	0.375	11.69	13.07	11.64	12.13	0.312	1.613
	0.625	7.32	8.81	7.58	7.90	0.203	1.051
	0.875	4.44	5.28	3.53	4.42	0.114	0.587
28	0.375	10.82	10.11	11.45	10.79	0.278	1.435
	0.625	6.09	4.94	5.41	5.48	0.141	0.729
	0.875	4.57	2.12	2.37	3.02	0.078	0.401
56	0.375	7.63	6.00	9.27	7.63	0.196	1.015
	0.625	4.24	3.34	5.20	4.26	0.110	0.567
	0.875	2.09	1.44	2.79	2.10	0.054	0.280
91	0.375	8.23	7.92	7.14	7.76	0.200	1.032
	0.625	3.76	3.71	4.06	3.84	0.099	0.511
	0.875	2.53	2.32	1.47	2.10	0.054	0.280
182	0.375	6.03	6.68	5.88	6.20	0.159	0.824
	0.625	3.46	3.11	2.52	3.03	0.078	0.403
	0.875	1.56	0.99	1.67	1.41	0.036	0.187
364	0.375	3.97	3.08	2.66	3.24	0.083	0.430
	0.625	2.46	1.19	1.34	1.66	0.043	0.221
	0.875	0.45	0.83	0.56	0.61	0.016	0.081

Elect. Tests 30. RMT Chloride Profile Testing Results (CPR11 to CPR12 Mixtures).

MIX CPR11

Concrete Unit W. 142.82 pcf

Binder Unit W. 752.00 lb/yd^3

Test	**Depth**	**NaCl (lb/yd^3)**				**%NaCl**	
(Day)	**(in)**	**A**	**B**	**C**	**AVG**	**(Conc.)**	**(Binder)**
17	0.375	13.48	9.17	10.86	11.17	0.290	1.485
	0.625	4.62	2.37	3.35	3.45	0.089	0.458
	0.875	1.34	0.50	1.74	1.19	0.031	0.159
28	0.375	8.22	9.42	10.50	9.38	0.243	1.247
	0.625	1.97	5.85	7.85	5.22	0.135	0.695
	0.875	0.74	2.08	2.74	1.85	0.048	0.246
56	0.375	13.96	11.80	13.48	13.08	0.339	1.739
	0.625	9.19	6.12	8.85	8.05	0.209	1.071
	0.875	3.96	3.22	2.91	3.36	0.087	0.447
91	0.375	11.21	9.72	15.45	12.12	0.314	1.612
	0.625	4.06	3.59	8.46	5.37	0.139	0.714
	0.875	1.65	2.70	3.28	2.54	0.066	0.338
182	0.375	12.99	9.99	8.44	10.47	0.272	1.392
	0.625	4.80	1.97	2.45	3.07	0.080	0.409
	0.875	1.74	2.82	1.98	2.18	0.057	0.290
365	0.125	23.87	21.19	25.09	23.38	0.606	3.110
	0.375	10.66	8.80	8.48	9.31	0.241	1.238
	0.625	2.92	3.67	4.82	3.81	0.099	0.506
	0.875	2.01	1.96	2.44	2.13	0.055	0.284
	1.125	1.04	2.65	1.95	1.88	0.049	0.250
	1.375	0.66	1.62	0.88	1.05	0.027	0.140
	1.625	0.40	0.99	0.52	0.63	0.016	0.084
	1.875	0.40	0.76	0.41	0.52	0.014	0.070

MIX CPR12

Concrete Unit W. 139.58 pcf

Binder Unit W. 752.00 lb/yd^3

Test	**Depth**	**NaCl (lb/yd^3)**				**%NaCl**	
(Day)	**(in)**	**A**	**B**	**C**	**AVG**	**(Conc.)**	**(Binder)**
14	0.375	4.73	5.37	3.56	4.55	0.121	0.605
	0.625	1.38	2.02	1.31	1.57	0.042	0.209
	0.875	0.54	0.85	0.46	0.62	0.016	0.082
28	0.375	15.95	18.82	15.27	16.68	0.443	2.218
	0.625	9.35	11.25	11.52	10.71	0.284	1.424
	0.875	4.77	7.07	4.75	5.53	0.147	0.735
56	0.375	3.92	4.45	3.74	4.04	0.107	0.537
	0.625	1.08	0.80	1.59	1.16	0.031	0.154
	0.875	0.76	0.52	0.65	0.64	0.017	0.086
91	0.375	18.41	16.08	12.74	15.74	0.418	2.093
	0.625	10.36	5.09	4.11	6.52	0.173	0.867
	0.875	3.65	1.79	1.01	2.15	0.057	0.286
182	0.375	14.19	14.45	11.16	13.27	0.352	1.764
	0.625	4.37	5.82	3.06	4.42	0.117	0.587
	0.875	1.12	3.61	0.96	1.90	0.050	0.252
364	0.125	31.59	31.26	28.16	30.34	0.805	4.034
	0.375	15.02	17.84	15.33	16.06	0.426	2.136
	0.625	9.70	8.64	8.21	8.85	0.235	1.177
	0.875	6.38	3.02	2.68	4.03	0.107	0.535
	1.125	1.92	1.01	1.01	1.31	0.035	0.175
	1.375	1.01	0.54	0.40	0.65	0.017	0.086
	1.625	0.56	0.39	0.46	0.47	0.012	0.063
	1.875	0.49	0.55	0.39	0.48	0.013	0.064

Elect. Tests 31. RMT Chloride Profile Testing Results (CPR13 to CPR17 Mixtures).

MIX CPR13

Concrete Unit W. 140.49 pcf

Binder Unit W. 569.70 lb/yd^3

Test	Depth	NaCl (lb/yd^3)				%NaCl	
(Day)	(in)	A	B	C	AVG	(Conc.)	(Binder)
14	0.375	11.20	9.95	8.38	9.84	0.259	1.728
	0.625	1.57	2.90	0.00	2.23	0.059	0.392
	0.875	0.73	0.76	0.00	0.74	0.020	0.131
28	0.375	7.41	3.52	2.02	4.32	0.114	0.758
	0.625	0.62	0.95	0.61	0.73	0.019	0.128
	0.875	0.29	0.45	1.88	0.87	0.023	0.153
56	0.375	16.92	15.79	17.15	16.62	0.438	2.917
	0.625	12.47	10.82	11.15	11.48	0.303	2.015
	0.875	0.00	9.86	6.64	8.25	0.217	1.448
91	0.375	19.54	23.25	29.34	24.04	0.634	4.220
	0.625	11.22	16.55	20.95	16.24	0.428	2.850
	0.875	9.36	10.11	14.15	11.21	0.295	1.967
182	0.375	18.43	15.36	16.26	16.68	0.440	2.929
	0.625	13.07	10.57	11.36	11.67	0.308	2.048
	0.875	9.53	8.49	5.30	7.77	0.205	1.364
364	0.375	15.04	14.42	14.14	14.53	0.383	2.551
	0.625	10.11	11.98	8.37	10.15	0.268	1.782
	0.875	5.69	8.84	3.80	6.11	0.161	1.073

MIX CPR15

Concrete Unit W. 148.64 pcf

Binder Unit W. 565.00 lb/yd^3

Test	Depth	NaCl (lb/yd^3)				%NaCl	
(Day)	(in)	A	B	C	AVG	(Conc.)	(Binder)
14	0.375	8.47	14.22	0.00	11.34	0.283	2.008
	0.625	6.74	8.33	0.56	5.21	0.130	0.922
	0.875	3.48	3.42	0.83	2.58	0.064	0.456
28	0.375	27.21	6.27	7.45	13.64	0.340	2.414
	0.625	11.68	2.43	3.89	6.00	0.150	1.062
	0.875	11.29	0.77	0.60	4.22	0.105	0.747
56	0.375	16.72	15.10	17.03	16.28	0.406	2.882
	0.625	12.03	11.77	16.75	13.52	0.337	2.393
	0.875	10.16	9.06	11.42	10.21	0.254	1.807
91	0.375	13.29	33.38	31.69	26.12	0.651	4.623
	0.625	12.56	22.38	21.20	18.71	0.466	3.312
	0.875	10.80	18.18	16.18	15.05	0.375	2.664
182	0.375	17.31	14.58	10.05	13.98	0.348	2.474
	0.625	8.64	9.35	5.07	7.68	0.191	1.360
	0.875	2.95	3.70	2.62	3.09	0.077	0.546
364	0.375	15.67	15.56	16.80	16.01	0.399	2.833
	0.625	13.32	11.52	13.62	12.82	0.319	2.269
	0.875	7.74	7.33	8.72	7.93	0.198	1.404

MIX CPR16

Concrete Unit W. 145.01 pcf

Binder Unit W. 807.40 lb/yd^3

Test	Depth	NaCl (lb/yd^3)				%NaCl	
(Day)	(in)	A	B	C	AVG	(Conc.)	(Binder)
14	0.375	4.30	4.20	4.70	4.40	0.112	0.545
	0.625	1.58	1.49	1.48	1.52	0.039	0.188
	0.875	0.56	1.00	0.51	0.69	0.018	0.086
28	0.375	3.15	3.27	4.29	3.57	0.091	0.442
	0.625	0.82	0.79	1.22	0.94	0.024	0.117
	0.875	0.57	0.34	0.56	0.49	0.013	0.061
56	0.375	7.72	8.34	10.75	8.94	0.228	1.107
	0.625	4.53	3.80	5.18	4.50	0.115	0.558
	0.875	3.08	1.43	1.96	2.16	0.055	0.267
91	0.375	7.16	7.19	8.75	7.70	0.197	0.954
	0.625	4.24	4.25	3.46	3.98	0.102	0.493
	0.875	1.83	2.03	1.63	1.83	0.047	0.227
182	0.375	10.98	8.76	9.70	9.81	0.251	1.216
	0.625	5.37	4.77	8.88	6.34	0.162	0.785
	0.875	4.45	3.26	5.43	4.38	0.112	0.542
364	0.375	4.87	7.35	5.06	5.76	0.147	0.713
	0.625	3.12	4.73	2.59	3.48	0.089	0.431
	0.875	3.01	3.25	1.72	2.66	0.068	0.329

MIX CPR17

Concrete Unit W. 143.08 pcf

Binder Unit W. 840.00 lb/yd^3

Test	Depth	NaCl (lb/yd^3)				%NaCl	
(Day)	(in)	A	B	C	AVG	(Conc.)	(Binder)
14	0.375	3.97	4.98	7.44	5.46	0.141	0.650
	0.625	0.63	1.10	1.67	1.13	0.029	0.135
	0.875	0.37	0.77	0.28	0.47	0.012	0.056
28	0.375	12.54	1.31	16.87	10.24	0.265	1.219
	0.625	10.14	5.75	11.73	9.21	0.238	1.096
	0.875	2.03	2.35	6.01	3.46	0.090	0.412
56	0.375	7.04	10.20	6.39	7.88	0.204	0.938
	0.625	3.01	3.91	2.70	3.20	0.083	0.381
	0.875	0.59	1.56	0.74	0.96	0.025	0.115
91	0.375	16.43	6.52	19.33	14.09	0.365	1.678
	0.625	9.54	3.61	11.53	8.23	0.213	0.979
	0.875	4.84	2.70	7.22	4.92	0.127	0.586
182	0.375	9.65	10.22	8.30	9.39	0.243	1.118
	0.625	5.91	8.25	6.22	6.79	0.176	0.809
	0.875	2.61	2.54	2.44	2.53	0.065	0.301
364	0.375	8.08	5.46	9.45	7.66	0.198	0.912
	0.625	3.09	2.76	4.10	3.32	0.086	0.395
	0.875	2.82	1.60	1.97	2.13	0.055	0.253

Elect. Tests 32. RMT Chloride Profile Testing Results (CPR18 to CPR21 Mixtures).

MIX CPR18
Concrete Unit W. 148.77 pcf
Binder Unit W. 842.00 lb/yd^3

Test	**Depth**	**NaCl (lb/yd^3)**				**%NaCl**	
(Day)	**(in)**	**A**	**B**	**C**	**AVG**	**(Conc.)**	**(Binder)**
14	0.375	5.29	8.40	9.13	7.61	0.189	0.903
	0.625	0.47	1.12	1.14	0.91	0.023	0.108
	0.875	0.58	0.37	0.62	0.52	0.013	0.062
28	0.375	13.76	11.12	13.74	12.87	0.321	1.529
	0.625	6.41	4.26	7.73	6.13	0.153	0.728
	0.875	1.32	1.44	2.64	1.80	0.045	0.214
56	0.375	15.08	11.68	12.87	13.21	0.329	1.569
	0.625	8.31	5.10	7.37	6.92	0.172	0.822
	0.875	2.97	1.73	4.42	3.04	0.076	0.361
91	0.375	8.44	7.13	10.81	8.79	0.219	1.044
	0.625	2.80	2.75	5.00	3.52	0.088	0.418
	0.875	1.19	0.88	0.97	1.01	0.025	0.120
182	0.375	2.31	3.42	2.51	2.75	0.068	0.326
	0.625	1.87	1.02	1.17	1.35	0.034	0.161
	0.875	1.24	0.96	0.94	1.05	0.026	0.124
364	0.375	1.04	0.72	1.67	1.14	0.028	0.136
	0.625	0.77	0.65	0.78	0.73	0.018	0.087
	0.875	0.74	0.69	0.53	0.66	0.016	0.078

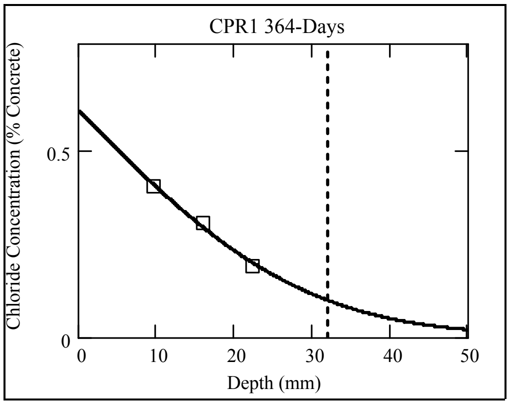
MIX CPR20
Concrete Unit W. 142.16 pcf
Binder Unit W. 1000.00 lb/yd^3

Test	**Depth**	**NaCl (lb/yd^3)**				**%NaCl**	
(Day)	**(in)**	**A**	**B**	**C**	**AVG**	**(Conc.)**	**(Binder)**
14	0.375	3.93	2.72	3.37	3.34	0.087	0.334
	0.625	0.34	1.30	0.48	0.70	0.018	0.070
	0.875	0.11	0.49	0.23	0.28	0.007	0.028
28	0.375	12.93	9.87	12.72	11.84	0.309	1.184
	0.625	4.81	4.22	6.91	5.31	0.138	0.531
	0.875	2.32	1.42	2.04	1.93	0.050	0.193
56	0.375	12.81	14.33	14.20	13.78	0.359	1.378
	0.625	6.28	9.26	6.84	7.46	0.194	0.746
	0.875	2.18	5.67	4.23	4.03	0.105	0.403
91	0.375	8.74	11.67	9.97	10.13	0.264	1.013
	0.625	3.58	4.79	3.99	4.12	0.107	0.412
	0.875	1.17	2.32	2.11	1.86	0.049	0.186
182	0.125	9.24	9.55	9.45	9.42	0.245	0.942
	0.375	2.92	2.39	2.20	2.50	0.065	0.250
	0.625	0.76	1.09	0.54	0.80	0.021	0.080
	0.875	0.27	0.55	0.31	0.37	0.010	0.037
364	0.375	4.25	3.23	3.79	3.76	0.098	0.376
	0.625	1.65	0.89	1.99	1.51	0.039	0.151
	0.875	1.29	1.01	1.58	1.29	0.034	0.129

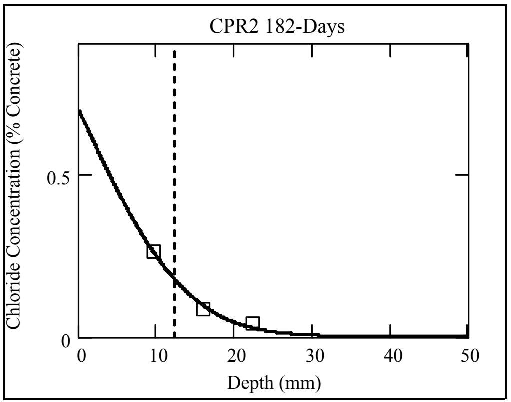
MIX CPR21
Concrete Unit W. 147.39 pcf
Binder Unit W. 935.00 lb/yd^3

Test	**Depth**	**NaCl (lb/yd^3)**				**%NaCl**	
(Day)	**(in)**	**A**	**B**	**C**	**AVG**	**(Conc.)**	**(Binder)**
14	0.375	9.49	7.90	6.90	8.09	0.203	0.866
	0.625	1.72	0.74	1.10	1.19	0.030	0.127
	0.875	0.44	0.62	0.58	0.55	0.014	0.059
28	0.375	13.70	14.23	14.67	14.20	0.357	1.518
	0.625	11.37	10.21	8.60	10.06	0.253	1.076
	0.875	4.13	5.20	3.90	4.41	0.111	0.472
56	0.375	14.24	11.17	16.29	13.90	0.349	1.487
	0.625	4.72	4.81	12.31	7.28	0.183	0.779
	0.875	1.62	2.57	10.98	5.06	0.127	0.541
91	0.375	17.24	16.56	14.27	16.02	0.403	1.714
	0.625	6.80	3.27	6.70	5.59	0.140	0.598
	0.875	2.31	1.07	2.83	2.07	0.052	0.221
182	0.375	7.43	7.57	4.65	6.55	0.165	0.700
	0.625	1.92	2.16	2.55	2.21	0.056	0.237
	0.875	1.55	1.10	1.86	1.50	0.038	0.161
364	0.375	1.82	1.82	2.26	1.97	0.049	0.210
	0.625	0.92	1.21	1.35	1.16	0.029	0.124
	0.875	0.85	1.18	1.17	1.07	0.027	0.114

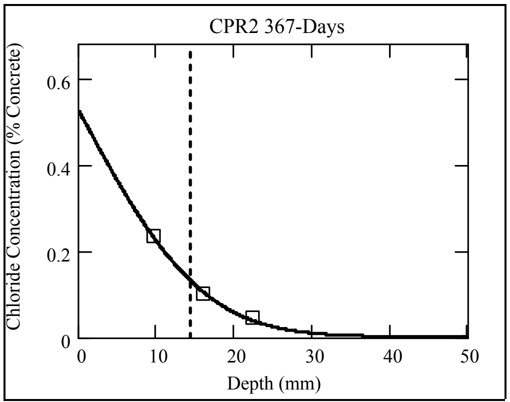
Elect. Tests 33. RMT Chloride Concentration by Concrete Weight at AgNO3 Color-Change Boundary (CPR1 to CPR3 Mixtures).



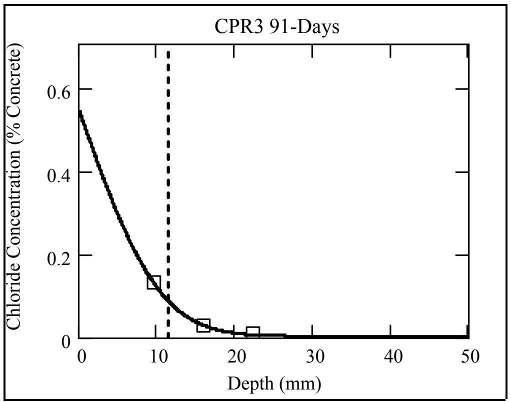
Diffusion(m^2/sec)	8.152E-12	**Background(% Con)**	0.004
Surface(% Con)	0.605	**R^2 Value**	0.995
Average Pene(mm)	31.852	**Derived % Cl(% Con)**	0.1



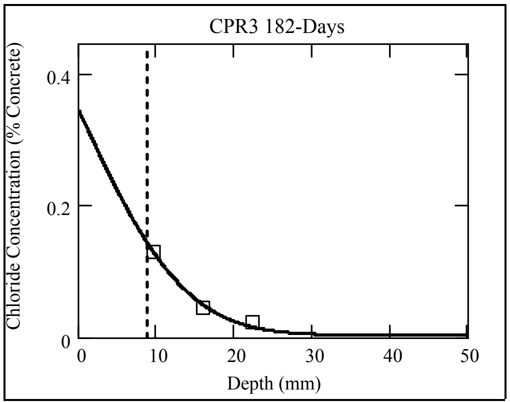
Diffusion(m^2/sec)	3.636E-12	**Background(% Con)**	0.002
Surface(% Con)	0.697	**R^2 Value**	0.995
Average Pene(mm)	12.192	**Derived % Cl(% Con)**	0.179



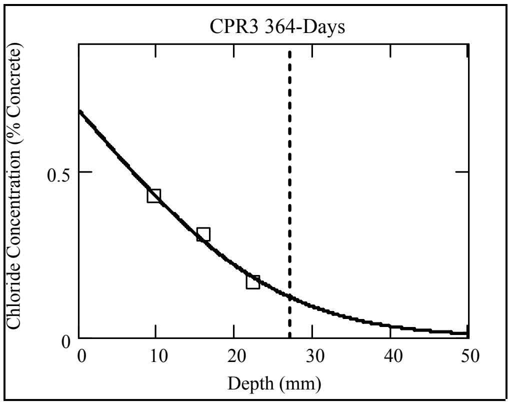
Diffusion(m^2/sec)	2.414E-12	**Background(% Con)**	0.002
Surface(% Con)	0.525	**R^2 Value**	0.998
Average Pene(mm)	14.173	**Derived % Cl(% Con)**	0.134



Diffusion(m^2/sec)	4.119E-12	**Background(% Con)**	0.003
Surface(% Con)	0.548	**R^2 Value**	0.999
Average Pene(mm)	11.379	**Derived % Cl(% Con)**	0.089

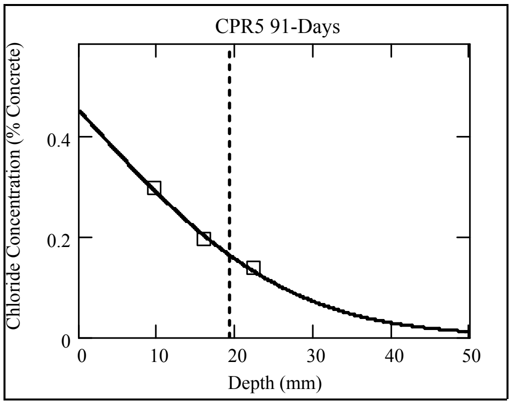


Diffusion(m^2/sec)	3.602E-12	**Background(% Con)**	0.003
Surface(% Con)	0.345	**R^2 Value**	0.996
Average Pene(mm)	8.738	**Derived % Cl(% Con)**	0.144

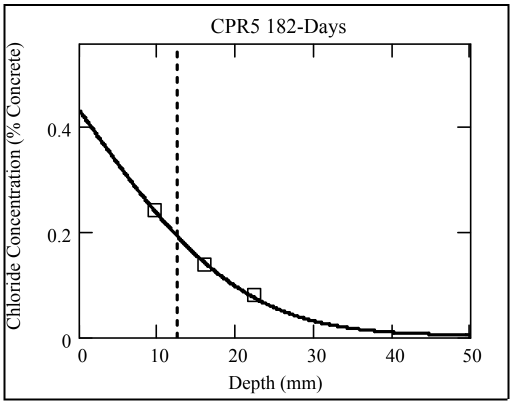


Diffusion(m^2/sec)	6.256E-12	**Background(% Con)**	0.003
Surface(% Con)	0.686	**R^2 Value**	0.991
Average Pene(mm)	27.000	**Derived % Cl(% Con)**	0.122

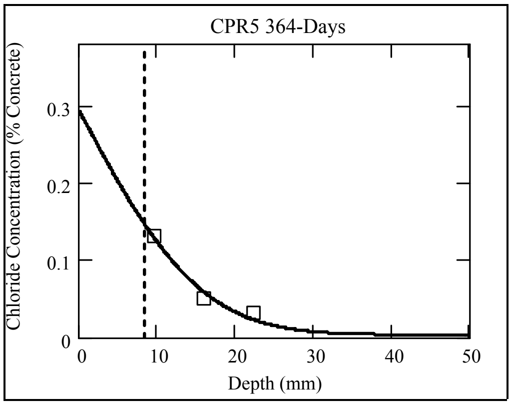
Elect. Tests 34. RMT Chloride Concentration by Concrete Weight at AgNO3 Color-Change Boundary (CPR5 to CPR6 Mixtures).



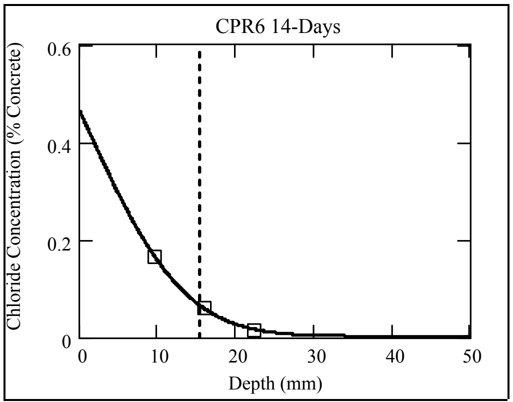
Diffusion(m^2/sec)	2.767E-11	**Background(% Con)**	0.004
Surface(% Con)	0.450	**R^2 Value**	0.996
Average Pene(mm)	19.253	**Derived % Cl(% Con)**	0.163



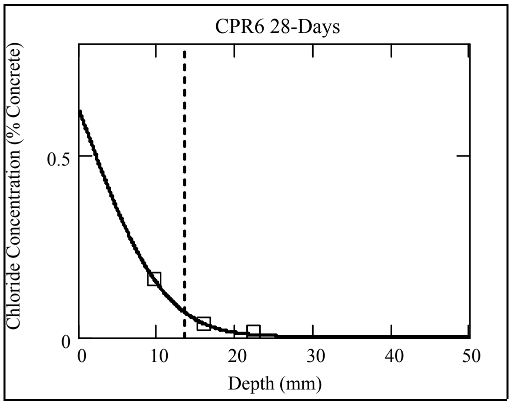
Diffusion(m^2/sec)	8.290E-12	**Background(% Con)**	0.004
Surface(% Con)	0.429	**R^2 Value**	0.999
Average Pene(mm)	12.370	**Derived % Cl(% Con)**	0.193



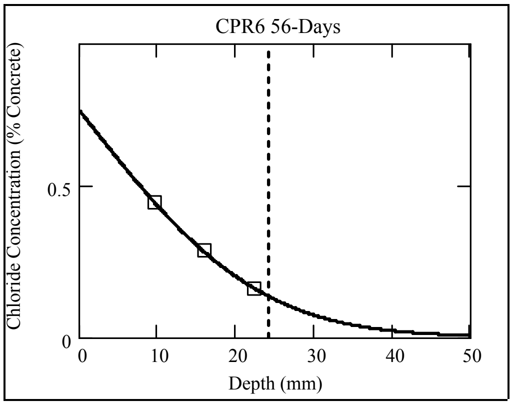
Diffusion(m^2/sec)	2.356E-12	**Background(% Con)**	0.004
Surface(% Con)	0.294	**R^2 Value**	0.986
Average Pene(mm)	8.357	**Derived % Cl(% Con)**	0.147



Diffusion(m^2/sec)	4.375E-11	**Background(% Con)**	0.003
Surface(% Con)	0.465	**R^2 Value**	1.000
Average Pene(mm)	15.316	**Derived % Cl(% Con)**	0.066

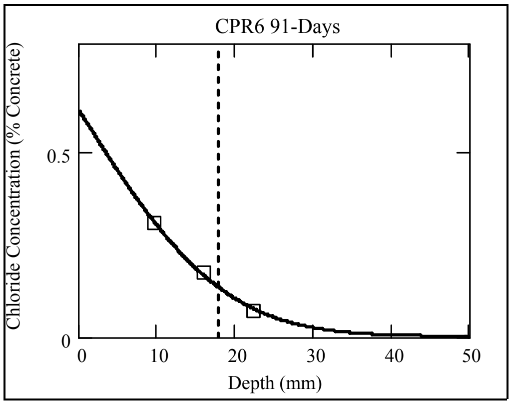


Diffusion(m^2/sec)	1.436E-11	**Background(% Con)**	0.003
Surface(% Con)	0.624	**R^2 Value**	0.998
Average Pene(mm)	13.386	**Derived % Cl(% Con)**	0.07

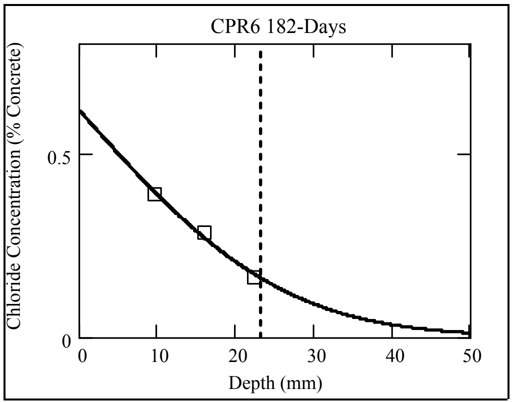


Diffusion(m^2/sec)	3.309E-11	**Background(% Con)**	0.003
Surface(% Con)	0.753	**R^2 Value**	1.000
Average Pene(mm)	23.978	**Derived % Cl(% Con)**	0.138

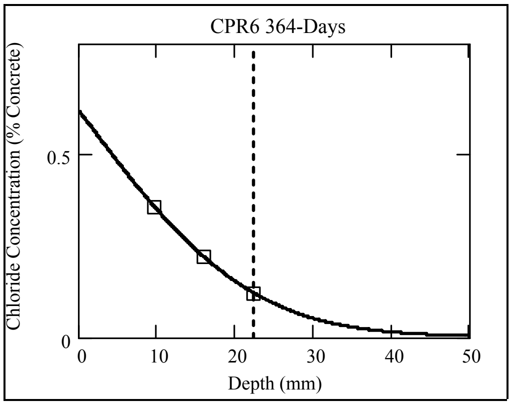
Elect. Tests 35. RMT Chloride Concentration by Concrete Weight at AgNO3 Color-Change Boundary (CPR6 to CPR7 Mixtures).



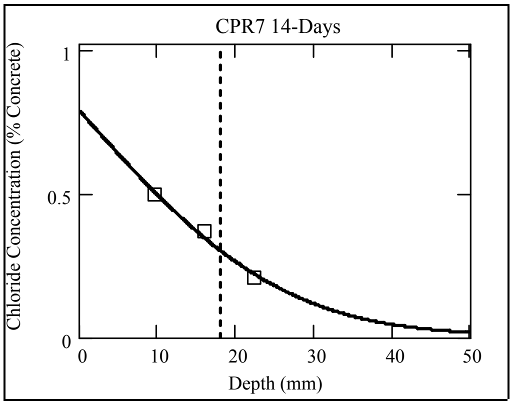
Diffusion(m^2/sec)	1.320E-11	**Background(% Con)**	0.003
Surface(% Con)	0.611	**R^2 Value**	0.997
Average Pene(mm)	17.653	**Derived % Cl(% Con)**	0.137



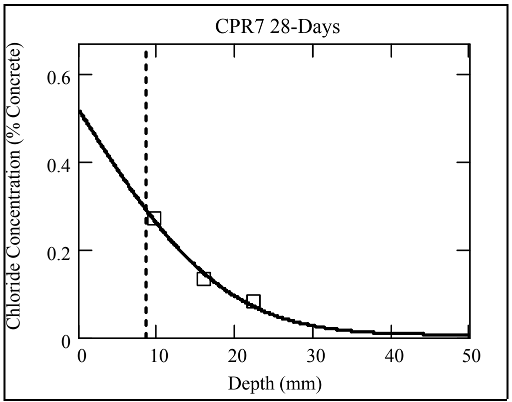
Diffusion(m^2/sec)	1.329E-11	**Background(% Con)**	0.003
Surface(% Con)	0.619	**R^2 Value**	0.992
Average Pene(mm)	23.114	**Derived % Cl(% Con)**	0.162



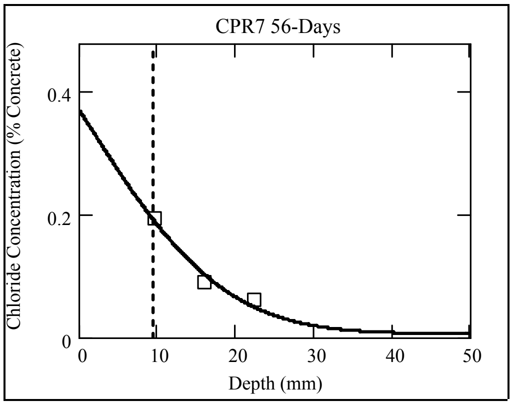
Diffusion(m^2/sec)	4.669E-12	**Background(% Con)**	0.003
Surface(% Con)	0.620	**R^2 Value**	1.000
Average Pene(mm)	22.327	**Derived % Cl(% Con)**	0.122



Diffusion(m^2/sec)	1.722E-10	**Background(% Con)**	0.006
Surface(% Con)	0.787	**R^2 Value**	0.992
Average Pene(mm)	17.831	**Derived % Cl(% Con)**	0.305

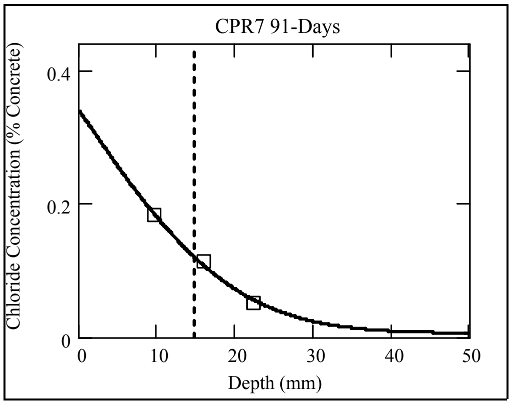


Diffusion(m^2/sec)	4.374E-11	**Background(% Con)**	0.006
Surface(% Con)	0.516	**R^2 Value**	0.990
Average Pene(mm)	8.433	**Derived % Cl(% Con)**	0.293

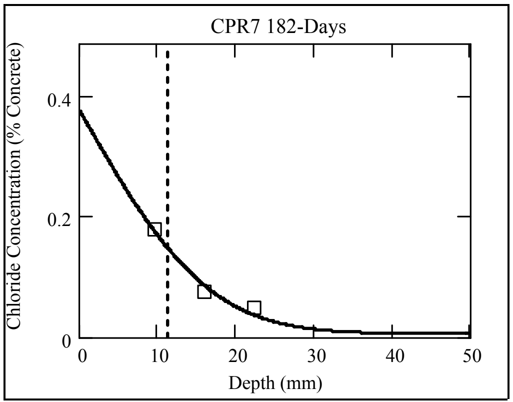


Diffusion(m^2/sec)	2.108E-11	**Background(% Con)**	0.006
Surface(% Con)	0.369	**R^2 Value**	0.984
Average Pene(mm)	9.347	**Derived % Cl(% Con)**	0.192

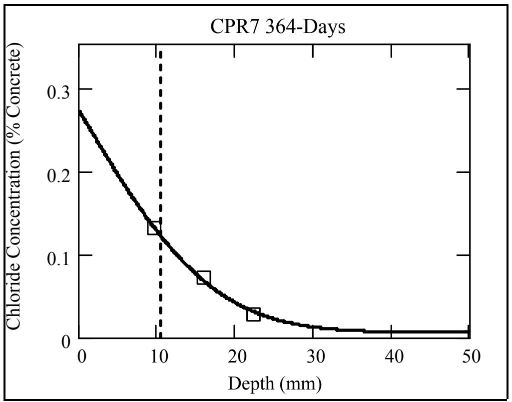
Elect. Tests 36. RMT Chloride Concentration by Concrete Weight at AgNO3 Color-Change Boundary (CPR7 to CPR8 Mixtures).



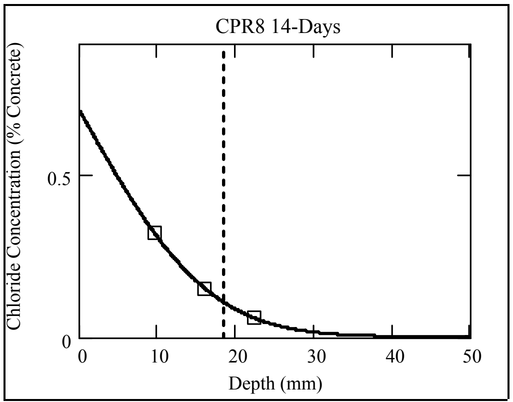
Diffusion(m^2/sec)	1.523E-11	**Background(% Con)**	0.006
Surface(% Con)	0.339	**R^2 Value**	0.996
Average Pene(mm)	14.580	**Derived % Cl(% Con)**	0.121



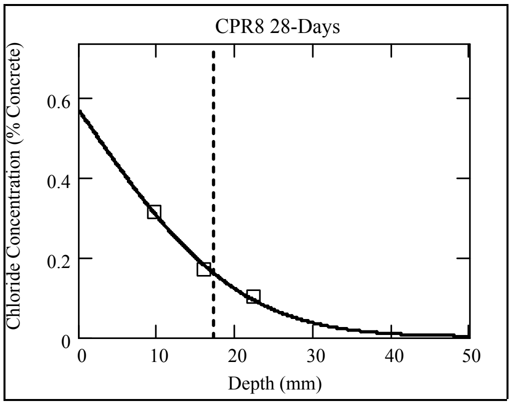
Diffusion(m^2/sec)	5.270E-12	**Background(% Con)**	0.006
Surface(% Con)	0.376	**R^2 Value**	0.987
Average Pene(mm)	11.151	**Derived % Cl(% Con)**	0.149



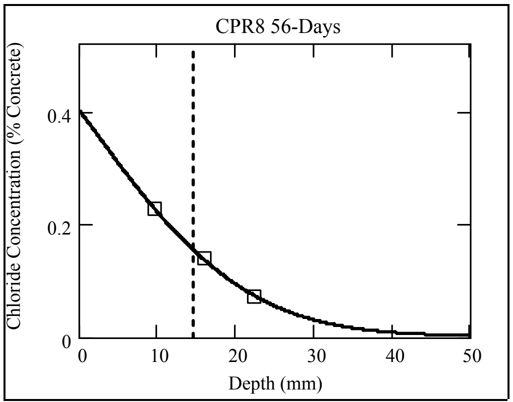
Diffusion(m^2/sec)	2.828E-12	**Background(% Con)**	0.006
Surface(% Con)	0.273	**R^2 Value**	0.998
Average Pene(mm)	10.439	**Derived % Cl(% Con)**	0.122



Diffusion(m^2/sec)	6.825E-11	**Background(% Con)**	0.003
Surface(% Con)	0.695	**R^2 Value**	1.000
Average Pene(mm)	18.288	**Derived % Cl(% Con)**	0.11

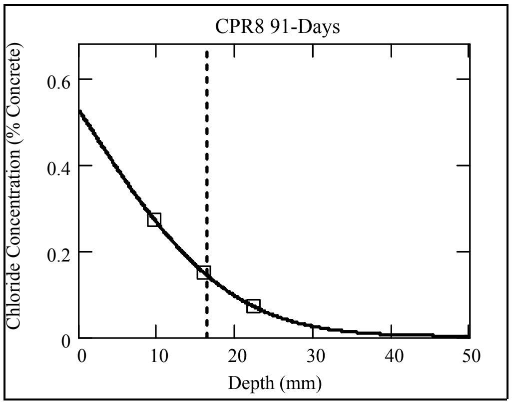


Diffusion(m^2/sec)	5.206E-11	**Background(% Con)**	0.003
Surface(% Con)	0.566	**R^2 Value**	0.995
Average Pene(mm)	17.018	**Derived % Cl(% Con)**	0.162

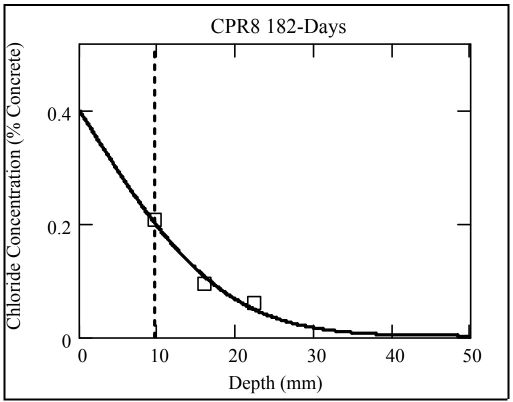


Diffusion(m^2/sec)	2.843E-11	**Background(% Con)**	0.003
Surface(% Con)	0.402	**R^2 Value**	1.000
Average Pene(mm)	14.427	**Derived % Cl(% Con)**	0.156

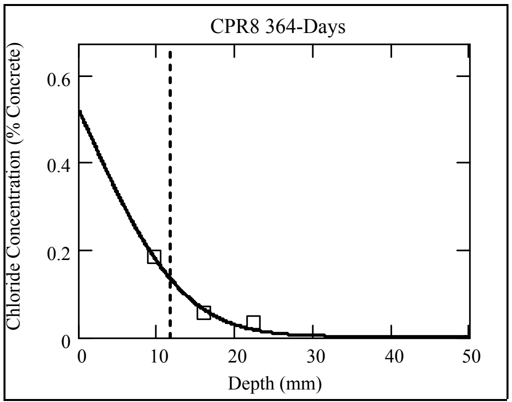
Elect. Tests 37. RMT Chloride Concentration by Concrete Weight at AgNO3 Color-Change Boundary (CPR8 to CPR9 Mixtures).


CPR8 91-Days

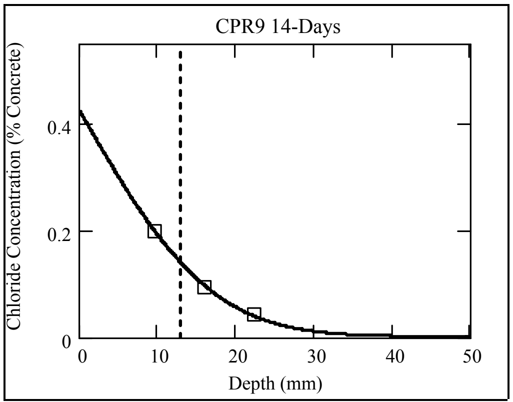
Diffusion(m^2/sec)	1.389E-11	**Background(% Con)**	0.003
Surface(% Con)	0.525	**R^2 Value**	1.000
Average Pene(mm)	16.307	**Derived % Cl(% Con)**	0.144


CPR8 182-Days

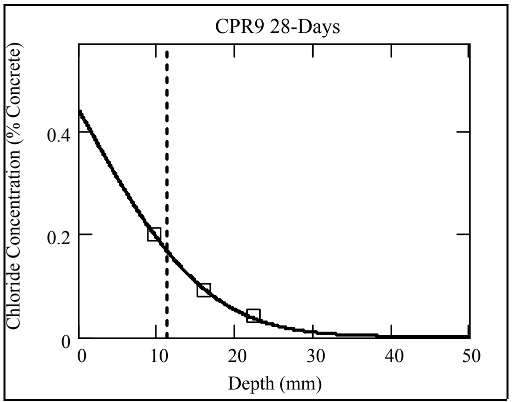
Diffusion(m^2/sec)	6.441E-12	**Background(% Con)**	0.003
Surface(% Con)	0.400	**R^2 Value**	0.987
Average Pene(mm)	9.500	**Derived % Cl(% Con)**	0.203


CPR8 364-Days

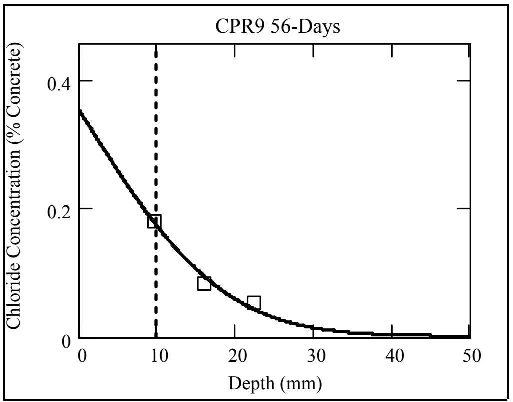
Diffusion(m^2/sec)	1.664E-12	**Background(% Con)**	0.003
Surface(% Con)	0.518	**R^2 Value**	0.990
Average Pene(mm)	11.608	**Derived % Cl(% Con)**	0.135


CPR9 14-Days

Diffusion(m^2/sec)	7.160E-11	**Background(% Con)**	0.002
Surface(% Con)	0.425	**R^2 Value**	1.000
Average Pene(mm)	12.903	**Derived % Cl(% Con)**	0.14

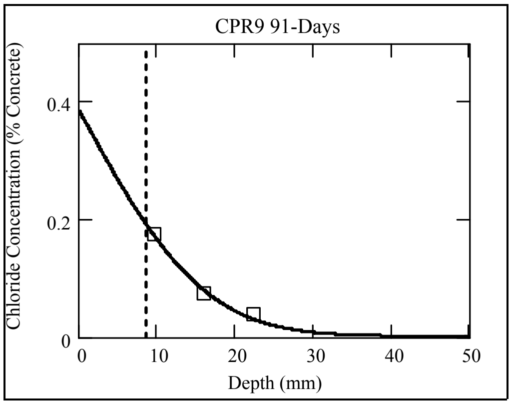

CPR9 28-Days

Diffusion(m^2/sec)	3.335E-11	**Background(% Con)**	0.002
Surface(% Con)	0.441	**R^2 Value**	0.998
Average Pene(mm)	11.227	**Derived % Cl(% Con)**	0.167

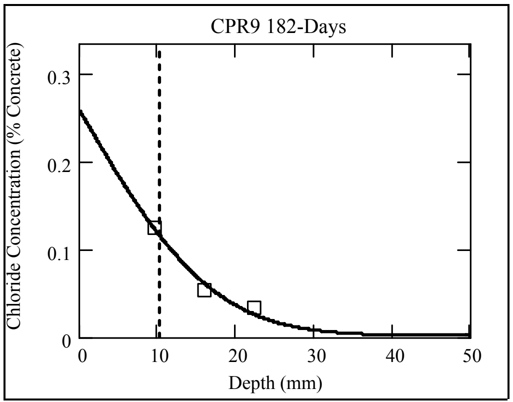

CPR9 56-Days

Diffusion(m^2/sec)	2.099E-11	**Background(% Con)**	0.002
Surface(% Con)	0.353	**R^2 Value**	0.989
Average Pene(mm)	9.703	**Derived % Cl(% Con)**	0.176

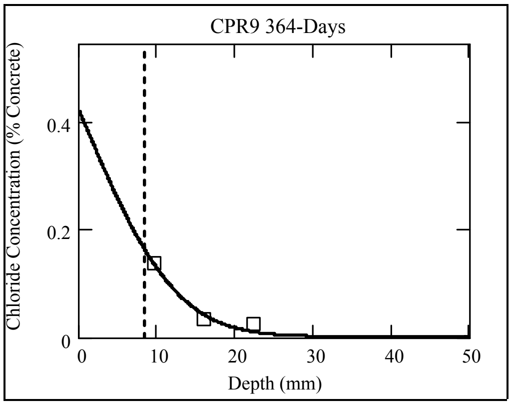
Elect. Tests 38. RMT Chloride Concentration by Concrete Weight at AgNO3 Color-Change Boundary (CPR9 to CPR10 Mixtures).



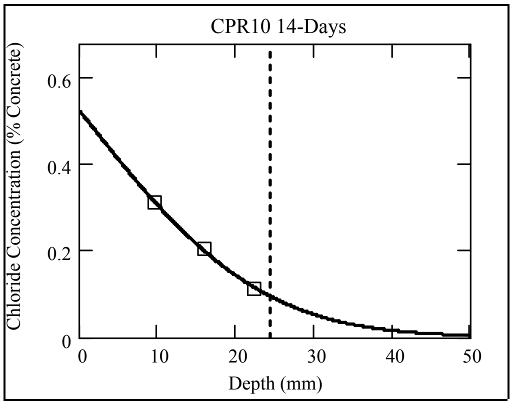
Diffusion(m^2/sec)	9.966E-12	**Background(% Con)**	0.002
Surface(% Con)	0.384	**R^2 Value**	0.995
Average Pene(mm)	8.560	**Derived % Cl(% Con)**	0.191



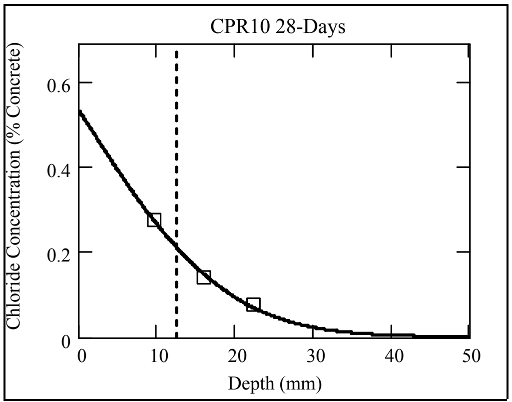
Diffusion(m^2/sec)	5.641E-12	**Background(% Con)**	0.002
Surface(% Con)	0.259	**R^2 Value**	0.987
Average Pene(mm)	10.236	**Derived % Cl(% Con)**	0.115



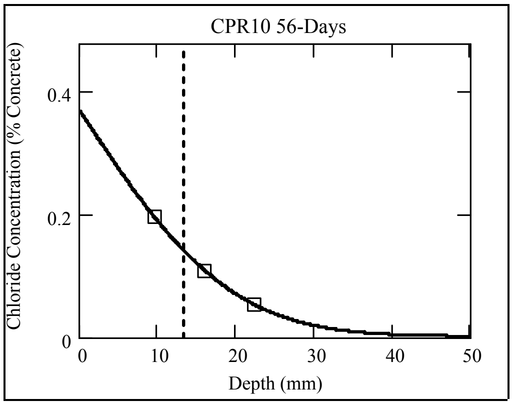
Diffusion(m^2/sec)	1.466E-12	**Background(% Con)**	0.002
Surface(% Con)	0.422	**R^2 Value**	0.984
Average Pene(mm)	8.357	**Derived % Cl(% Con)**	0.163



Diffusion(m^2/sec)	1.356E-10	**Background(% Con)**	0.002
Surface(% Con)	0.522	**R^2 Value**	0.999
Average Pene(mm)	24.206	**Derived % Cl(% Con)**	0.096

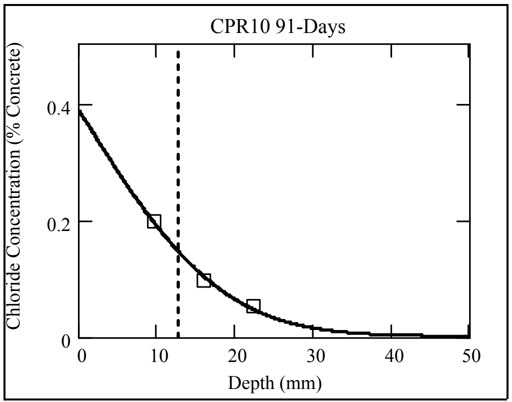


Diffusion(m^2/sec)	4.417E-11	**Background(% Con)**	0.002
Surface(% Con)	0.532	**R^2 Value**	0.997
Average Pene(mm)	12.370	**Derived % Cl(% Con)**	0.213

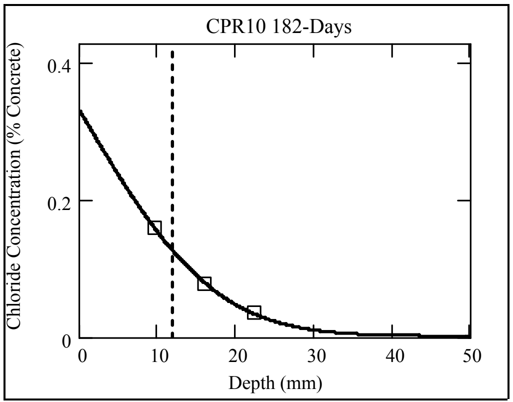


Diffusion(m^2/sec)	2.361E-11	**Background(% Con)**	0.002
Surface(% Con)	0.370	**R^2 Value**	1.000
Average Pene(mm)	13.157	**Derived % Cl(% Con)**	0.143

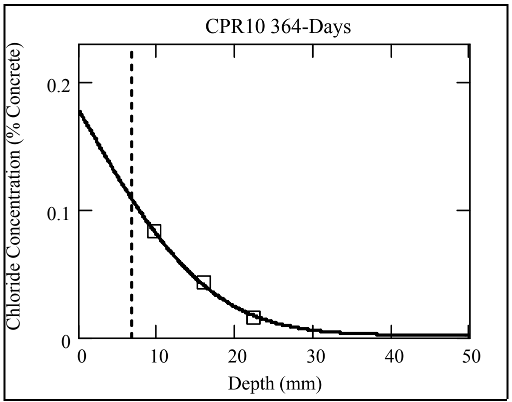
Elect. Tests 39. RMT Chloride Concentration by Concrete Weight at AgNO3 Color-Change Boundary (CPR10 to CPR11 Mixtures).



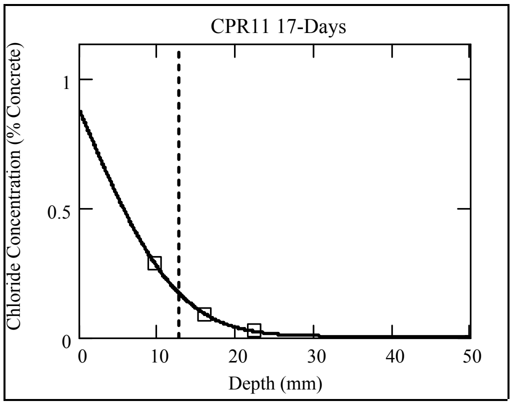
Diffusion(m^2/sec)	1.294E-11	**Background(% Con)**	0.002
Surface(% Con)	0.390	**R^2 Value**	0.997
Average Pene(mm)	12.573	**Derived % Cl(% Con)**	0.149



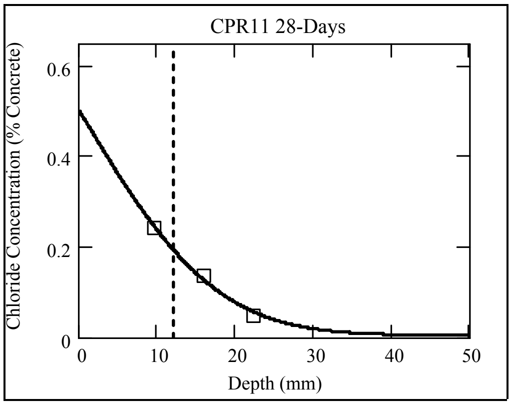
Diffusion(m^2/sec)	5.760E-12	**Background(% Con)**	0.002
Surface(% Con)	0.329	**R^2 Value**	1.000
Average Pene(mm)	11.786	**Derived % Cl(% Con)**	0.127



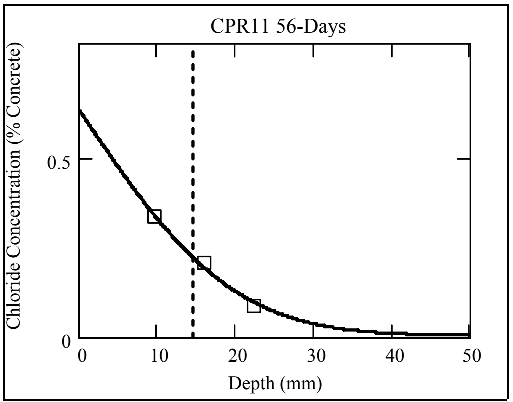
Diffusion(m^2/sec)	2.700E-12	**Background(% Con)**	0.002
Surface(% Con)	0.178	**R^2 Value**	0.999
Average Pene(mm)	6.655	**Derived % Cl(% Con)**	0.109



Diffusion(m^2/sec)	3.191E-11	**Background(% Con)**	0.005
Surface(% Con)	0.879	**R^2 Value**	0.999
Average Pene(mm)	12.548	**Derived % Cl(% Con)**	0.175

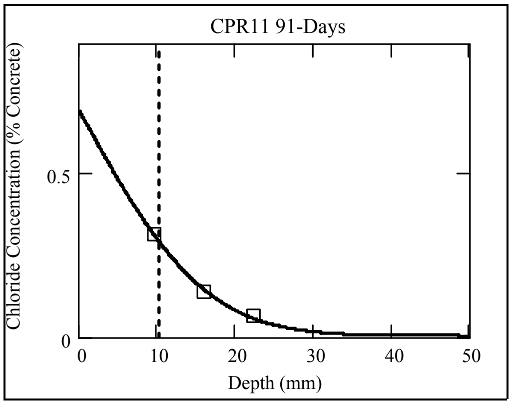


Diffusion(m^2/sec)	3.880E-11	**Background(% Con)**	0.005
Surface(% Con)	0.500	**R^2 Value**	0.996
Average Pene(mm)	11.963	**Derived % Cl(% Con)**	0.194

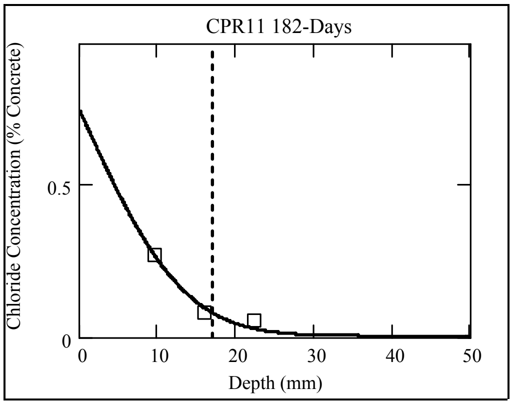


Diffusion(m^2/sec)	2.442E-11	**Background(% Con)**	0.005
Surface(% Con)	0.637	**R^2 Value**	0.995
Average Pene(mm)	14.529	**Derived % Cl(% Con)**	0.223

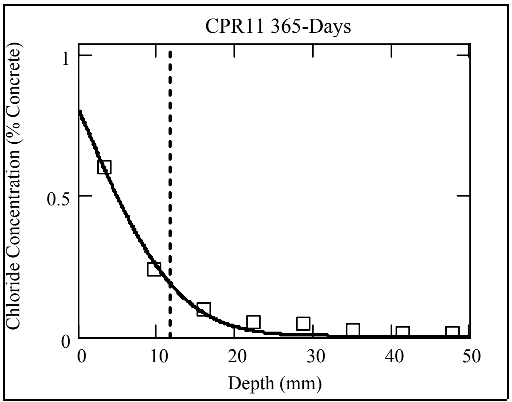
Elect. Tests 40. RMT Chloride Concentration by Concrete Weight at AgNO3 Color-Change Boundary (CPR11 to CPR12 Mixtures).



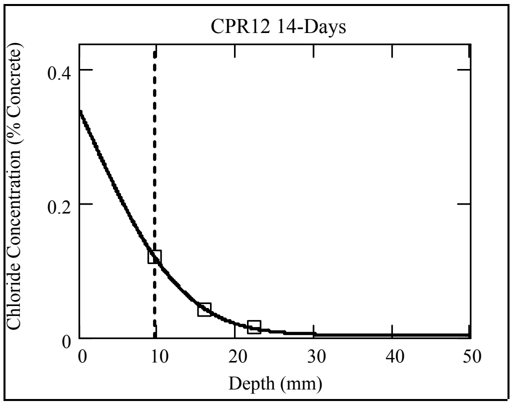
Diffusion(m^2/sec)	1.005E-11	**Background(% Con)**	0.005
Surface(% Con)	0.690	**R^2 Value**	0.998
Average Pene(mm)	10.058	**Derived % Cl(% Con)**	0.295



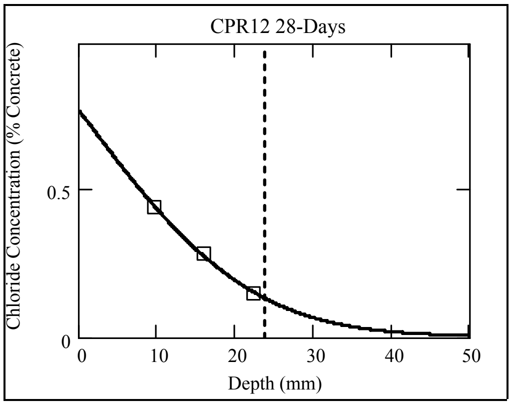
Diffusion(m^2/sec)	3.414E-12	**Background(% Con)**	0.005
Surface(% Con)	0.740	**R^2 Value**	0.983
Average Pene(mm)	16.967	**Derived % Cl(% Con)**	0.079



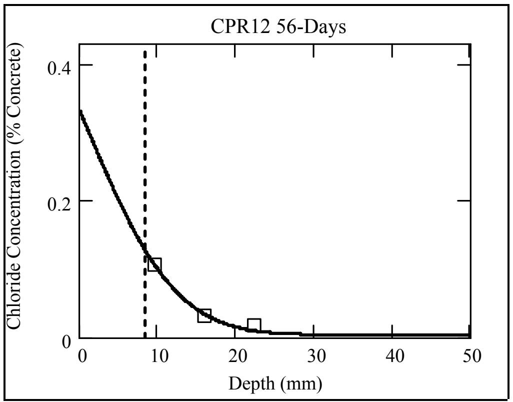
Diffusion(m^2/sec)	1.500E-12	**Background(% Con)**	0.005
Surface(% Con)	0.803	**R^2 Value**	0.996
Average Pene(mm)	11.659	**Derived % Cl(% Con)**	0.189



Diffusion(m^2/sec)	4.274E-11	**Background(% Con)**	0.004
Surface(% Con)	0.338	**R^2 Value**	0.999
Average Pene(mm)	9.474	**Derived % Cl(% Con)**	0.121

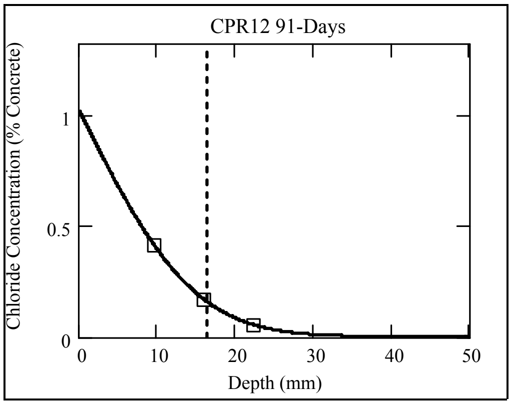


Diffusion(m^2/sec)	6.124E-11	**Background(% Con)**	0.004
Surface(% Con)	0.766	**R^2 Value**	0.999
Average Pene(mm)	23.673	**Derived % Cl(% Con)**	0.133

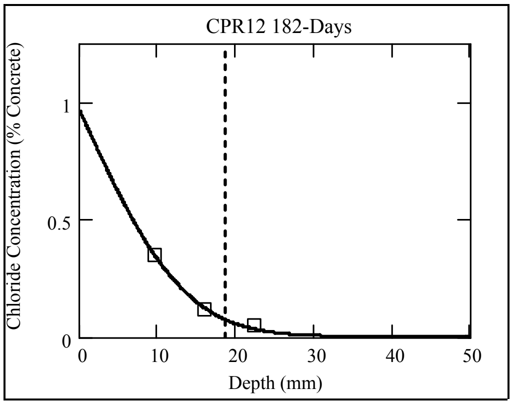


Diffusion(m^2/sec)	9.217E-12	**Background(% Con)**	0.004
Surface(% Con)	0.332	**R^2 Value**	0.995
Average Pene(mm)	8.357	**Derived % Cl(% Con)**	0.127

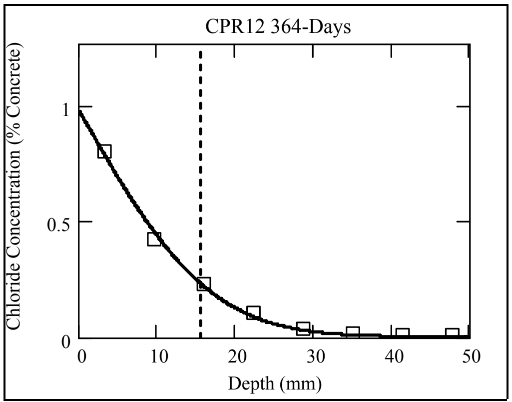
Elect. Tests 41. RMT Chloride Concentration by Concrete Weight at AgNO3 Color-Change Boundary (CPR12 to CPR15 Mixtures).



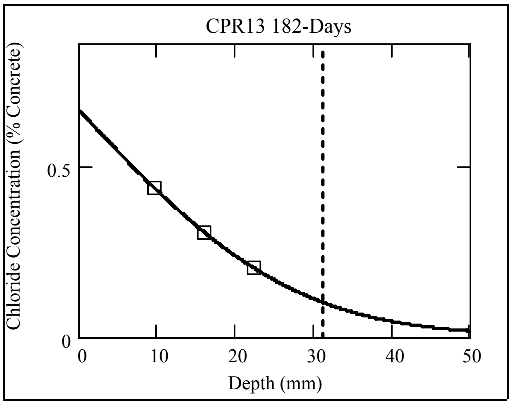
Diffusion(m^2/sec)	8.345E-12	**Background(% Con)**	0.004
Surface(% Con)	1.024	**R^2 Value**	1.000
Average Pene(mm)	16.332	**Derived % Cl(% Con)**	0.161



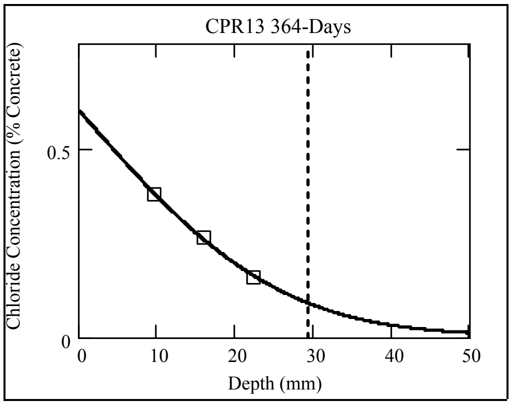
Diffusion(m^2/sec)	3.456E-12	**Background(% Con)**	0.004
Surface(% Con)	0.963	**R^2 Value**	0.997
Average Pene(mm)	18.567	**Derived % Cl(% Con)**	0.076



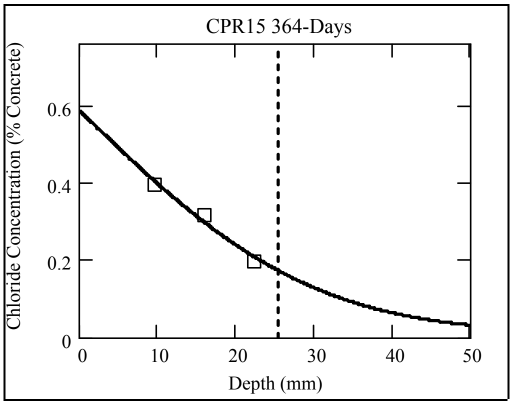
Diffusion(m^2/sec)	2.716E-12	**Background(% Con)**	0.004
Surface(% Con)	0.979	**R^2 Value**	0.999
Average Pene(mm)	15.392	**Derived % Cl(% Con)**	0.237



Diffusion(m^2/sec)	1.473E-11	**Background(% Con)**	0.005
Surface(% Con)	0.665	**R^2 Value**	1.000
Average Pene(mm)	30.963	**Derived % Cl(% Con)**	0.104

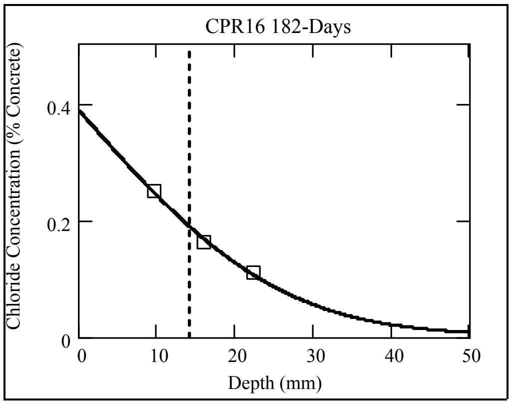


Diffusion(m^2/sec)	6.390E-12	**Background(% Con)**	0.005
Surface(% Con)	0.604	**R^2 Value**	0.999
Average Pene(mm)	29.159	**Derived % Cl(% Con)**	0.092

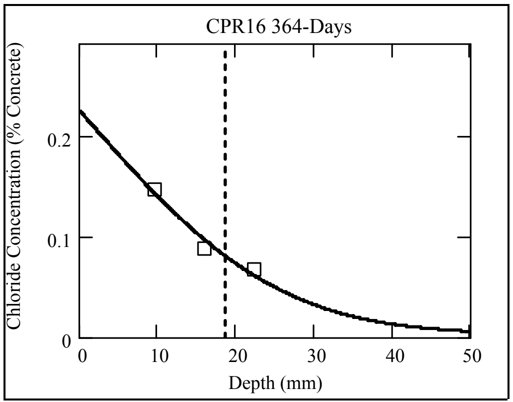


Diffusion(m^2/sec)	8.729E-12	**Background(% Con)**	0.013
Surface(% Con)	0.589	**R^2 Value**	0.985
Average Pene(mm)	25.375	**Derived % Cl(% Con)**	0.173

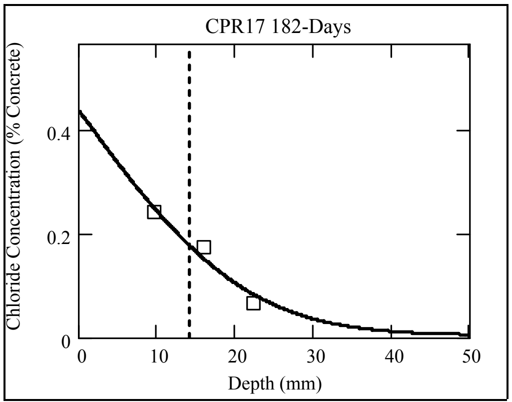
Elect. Tests 42. RMT Chloride Concentration by Concrete Weight at AgNO3 Color-Change Boundary (CPR16 to CPR18 Mixtures).


CPR16 182-Days

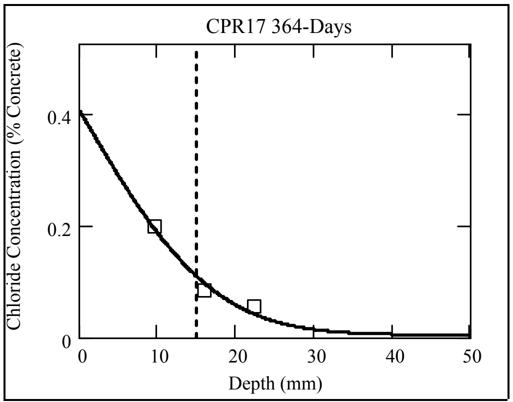
Diffusion(m^2/sec)	1.289E-11	**Background(% Con)**	0.003
Surface(% Con)	0.388	**R^2 Value**	0.996
Average Pene(mm)	14.021	**Derived % Cl(% Con)**	0.19


CPR16 364-Days

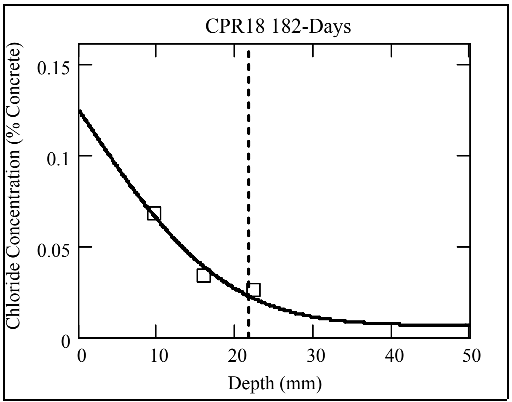
Diffusion(m^2/sec)	6.271E-12	**Background(% Con)**	0.003
Surface(% Con)	0.226	**R^2 Value**	0.981
Average Pene(mm)	18.567	**Derived % Cl(% Con)**	0.081


CPR17 182-Days

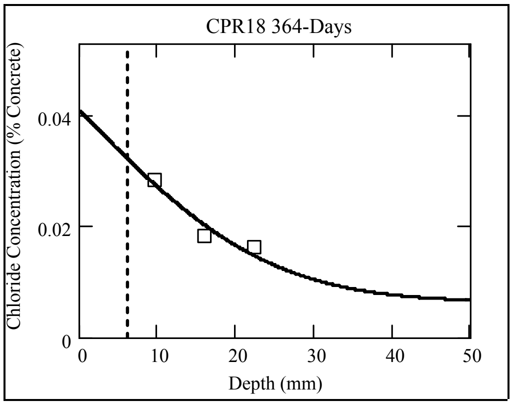
Diffusion(m^2/sec)	8.847E-12	**Background(% Con)**	0.005
Surface(% Con)	0.438	**R^2 Value**	0.971
Average Pene(mm)	14.021	**Derived % Cl(% Con)**	0.178


CPR17 364-Days

Diffusion(m^2/sec)	2.806E-12	**Background(% Con)**	0.005
Surface(% Con)	0.407	**R^2 Value**	0.987
Average Pene(mm)	14.808	**Derived % Cl(% Con)**	0.111

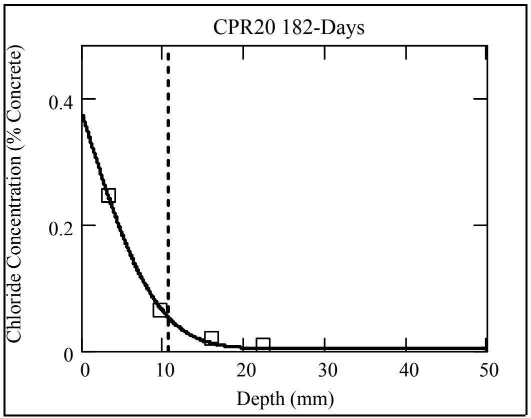

CPR18 182-Days

Diffusion(m^2/sec)	6.712E-12	**Background(% Con)**	0.006
Surface(% Con)	0.124	**R^2 Value**	0.976
Average Pene(mm)	21.565	**Derived % Cl(% Con)**	0.023

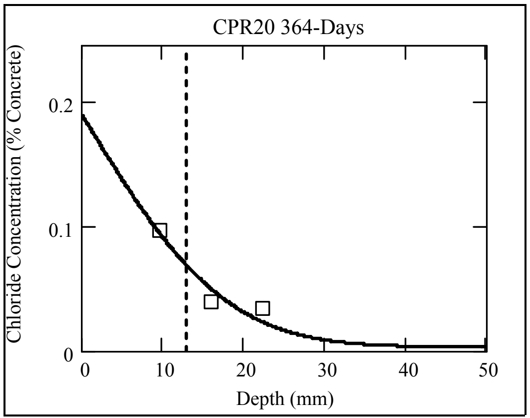

CPR18 364-Days

Diffusion(m^2/sec)	5.751E-12	**Background(% Con)**	0.006
Surface(% Con)	0.041	**R^2 Value**	0.956
Average Pene(mm)	6.071	**Derived % Cl(% Con)**	0.032

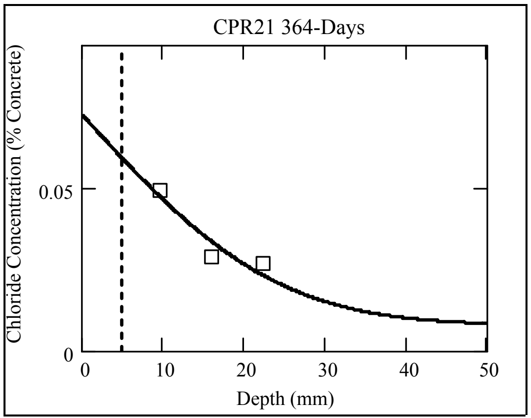
Elect. Tests 43. RMT Chloride Concentration by Concrete Weight at AgNO3 Color-Change Boundary (CPR20 to CPR21 Mixtures).


CPR20 182-Days

Diffusion(m^2/sec)	1.587E-12	**Background(% Con)**	0.003
Surface(% Con)	0.373	**R^2 Value**	0.999
Average Pene(mm)	10.541	**Derived % Cl(% Con)**	0.053

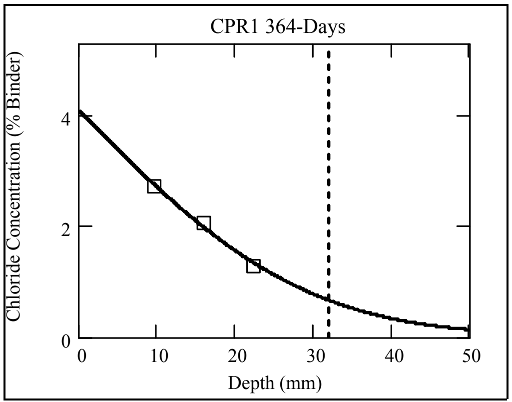

CPR20 364-Days

Diffusion(m^2/sec)	3.039E-12	**Background(% Con)**	0.003
Surface(% Con)	0.190	**R^2 Value**	0.956
Average Pene(mm)	12.776	**Derived % Cl(% Con)**	0.069

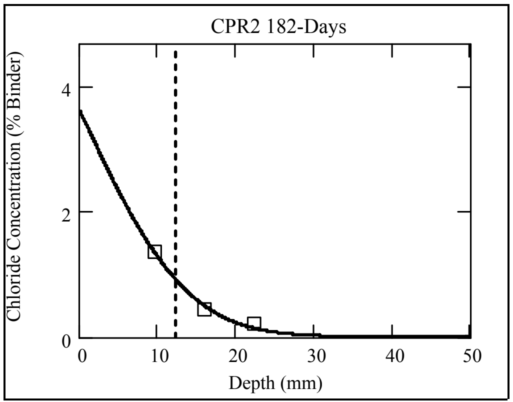

CPR21 364-Days

Diffusion(m^2/sec)	5.638E-12	**Background(% Con)**	0.008
Surface(% Con)	0.073	**R^2 Value**	0.939
Average Pene(mm)	4.877	**Derived % Cl(% Con)**	0.06

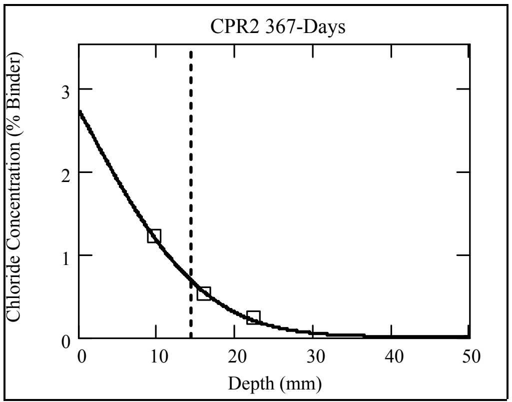
Elect. Tests 44. RMT Chloride Concentration by Binder Weight at AgNO3 Color-Change Boundary (CPR1 to CPR3 Mixtures).



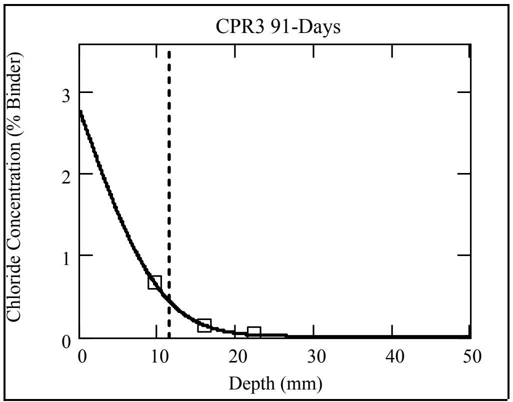
Diffusion(m^2/sec)	8.152E-12	**Background(% Bin)**	0.024
Surface(% Bin)	4.075	**R^2 Value**	0.995
Average Pene(mm)	31.852	**Derived % Cl(% Bin)**	0.67



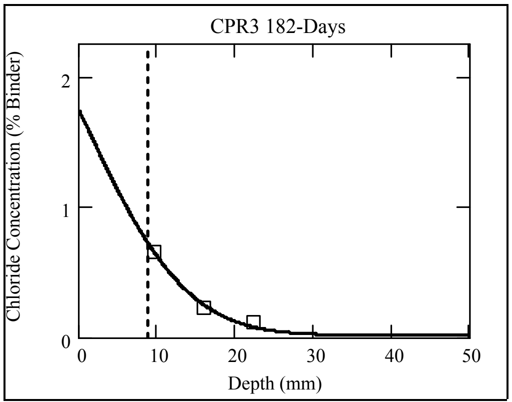
Diffusion(m^2/sec)	3.636E-12	**Background(% Bin)**	0.011
Surface(% Bin)	3.617	**R^2 Value**	0.995
Average Pene(mm)	12.192	**Derived % Cl(% Bin)**	0.927



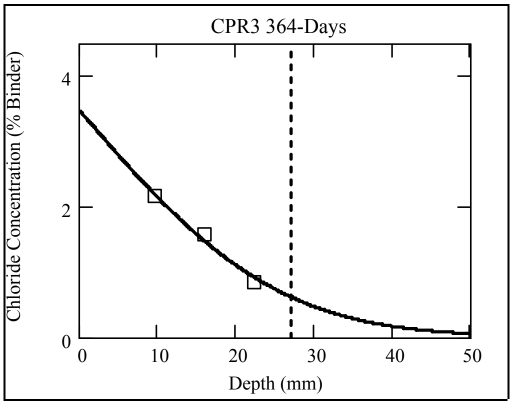
Diffusion(m^2/sec)	2.414E-12	**Background(% Bin)**	0.011
Surface(% Bin)	2.728	**R^2 Value**	0.998
Average Pene(mm)	14.173	**Derived % Cl(% Bin)**	0.695



Diffusion(m^2/sec)	4.119E-12	**Background(% Bin)**	0.017
Surface(% Bin)	2.760	**R^2 Value**	0.999
Average Pene(mm)	11.379	**Derived % Cl(% Bin)**	0.448

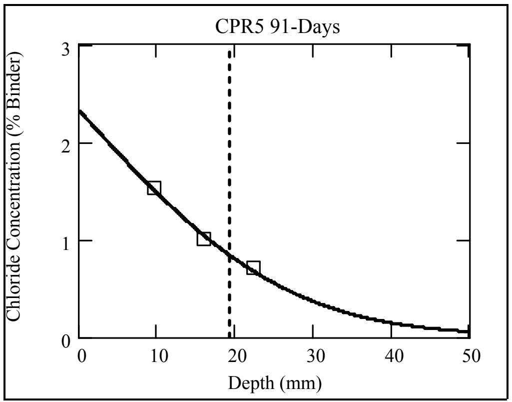


Diffusion(m^2/sec)	3.602E-12	**Background(% Bin)**	0.017
Surface(% Bin)	1.739	**R^2 Value**	0.996
Average Pene(mm)	8.738	**Derived % Cl(% Bin)**	0.726

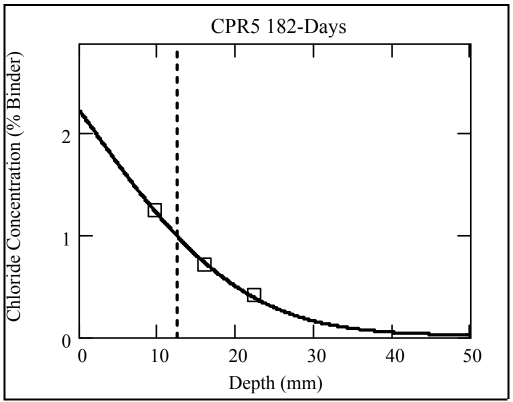


Diffusion(m^2/sec)	6.256E-12	**Background(% Bin)**	0.017
Surface(% Bin)	3.456	**R^2 Value**	0.991
Average Pene(mm)	27.000	**Derived % Cl(% Bin)**	0.613

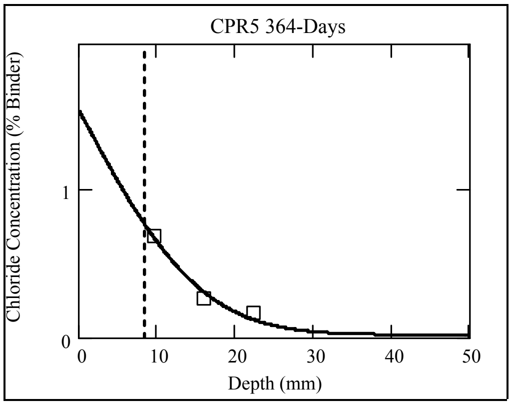
Elect. Tests 45. RMT Chloride Concentration by Binder Weight at AgNO3 Color-Change Boundary (CPR5 to CPR6 Mixtures).



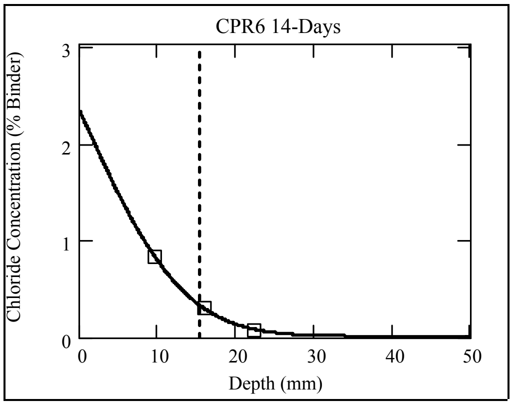
Diffusion(m^2/sec)	2.767E-11	**Background(% Bin)**	0.019
Surface(% Bin)	2.332	**R^2 Value**	0.996
Average Pene(mm)	19.253	**Derived % Cl(% Bin)**	0.842



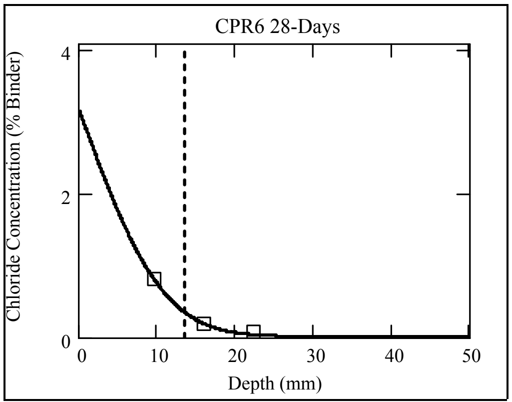
Diffusion(m^2/sec)	8.290E-12	**Background(% Bin)**	0.019
Surface(% Bin)	2.225	**R^2 Value**	0.999
Average Pene(mm)	12.370	**Derived % Cl(% Bin)**	0.998



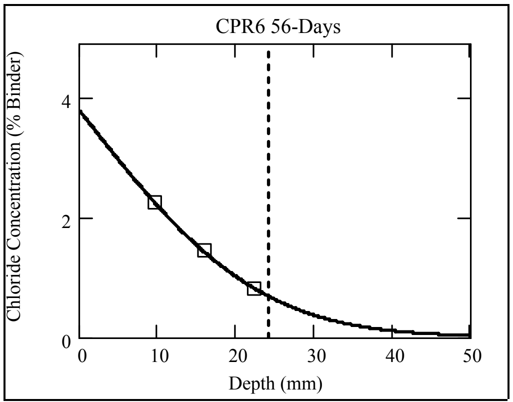
Diffusion(m^2/sec)	2.356E-12	**Background(% Bin)**	0.019
Surface(% Bin)	1.525	**R^2 Value**	0.986
Average Pene(mm)	8.357	**Derived % Cl(% Bin)**	0.761



Diffusion(m^2/sec)	4.375E-11	**Background(% Bin)**	0.014
Surface(% Bin)	2.345	**R^2 Value**	1.000
Average Pene(mm)	15.316	**Derived % Cl(% Bin)**	0.333

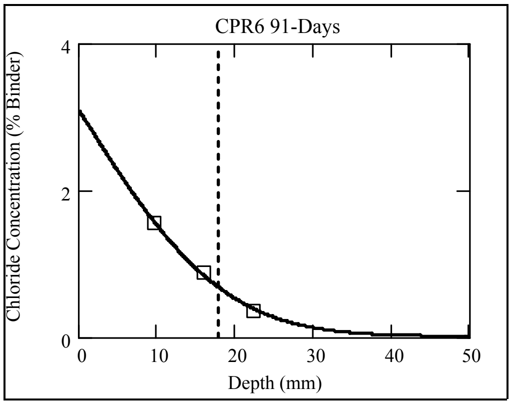


Diffusion(m^2/sec)	1.436E-11	**Background(% Bin)**	0.014
Surface(% Bin)	3.146	**R^2 Value**	0.998
Average Pene(mm)	13.386	**Derived % Cl(% Bin)**	0.353

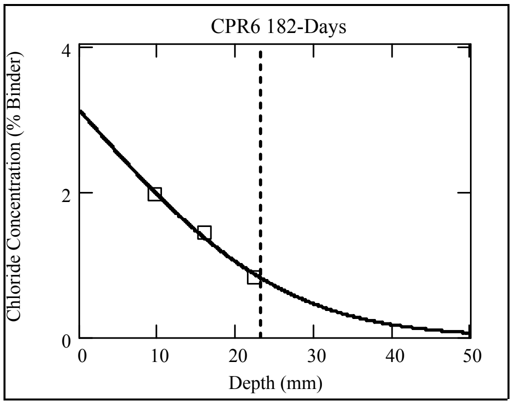


Diffusion(m^2/sec)	3.309E-11	**Background(% Bin)**	0.014
Surface(% Bin)	3.798	**R^2 Value**	1.000
Average Pene(mm)	23.978	**Derived % Cl(% Bin)**	0.696

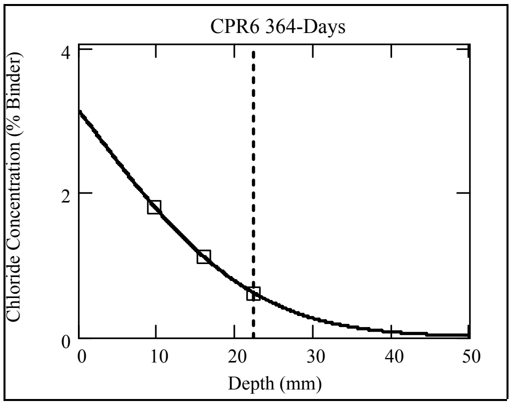
Elect. Tests 46. RMT Chloride Concentration by Binder Weight at AgNO3 Color-Change Boundary (CPR6 to CPR7 Mixtures).



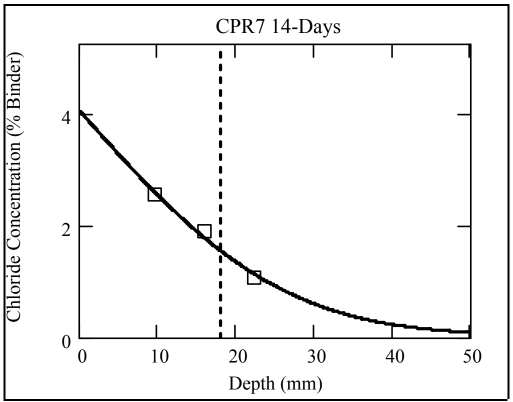
Diffusion(m^2/sec)	1.320E-11	**Background(% Bin)**	0.014
Surface(% Bin)	3.084	**R^2 Value**	0.997
Average Pene(mm)	17.653	**Derived % Cl(% Bin)**	0.691



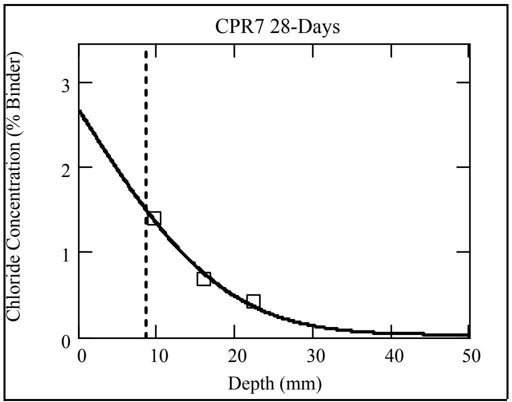
Diffusion(m^2/sec)	1.329E-11	**Background(% Bin)**	0.014
Surface(% Bin)	3.121	**R^2 Value**	0.992
Average Pene(mm)	23.114	**Derived % Cl(% Bin)**	0.816



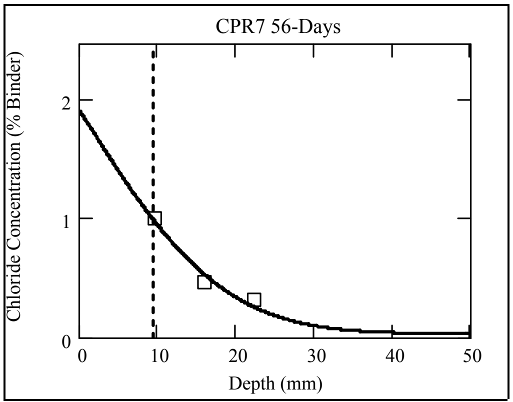
Diffusion(m^2/sec)	4.669E-12	**Background(% Bin)**	0.014
Surface(% Bin)	3.128	**R^2 Value**	1.000
Average Pene(mm)	22.327	**Derived % Cl(% Bin)**	0.614



Diffusion(m^2/sec)	1.722E-10	**Background(% Bin)**	0.031
Surface(% Bin)	4.062	**R^2 Value**	0.992
Average Pene(mm)	17.831	**Derived % Cl(% Bin)**	1.572

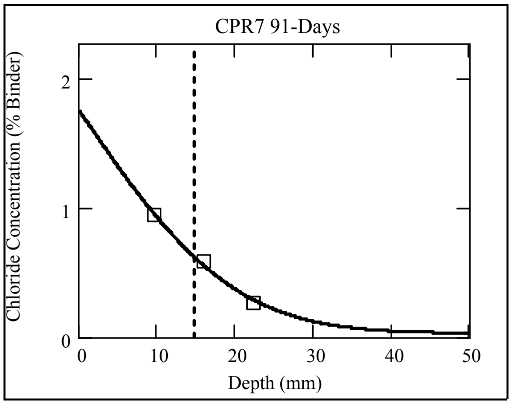


Diffusion(m^2/sec)	4.374E-11	**Background(% Bin)**	0.031
Surface(% Bin)	2.665	**R^2 Value**	0.990
Average Pene(mm)	8.433	**Derived % Cl(% Bin)**	1.511

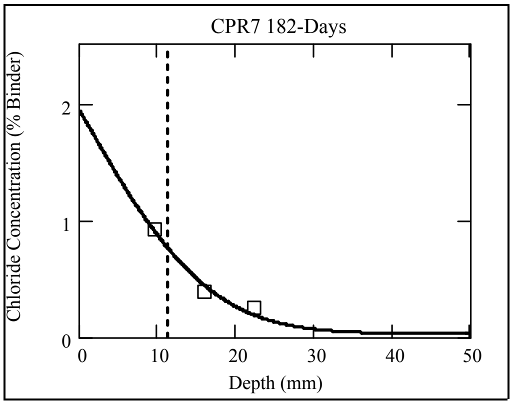


Diffusion(m^2/sec)	2.108E-11	**Background(% Bin)**	0.031
Surface(% Bin)	1.905	**R^2 Value**	0.984
Average Pene(mm)	9.347	**Derived % Cl(% Bin)**	0.992

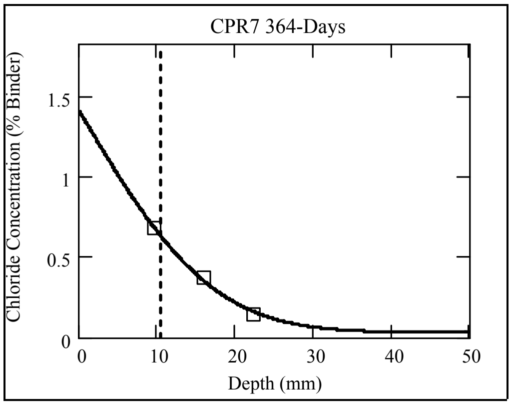
Elect. Tests 47. RMT Chloride Concentration by Binder Weight at AgNO3 Color-Change Boundary (CPR7 to CPR8 Mixtures).


CPR7 91-Days

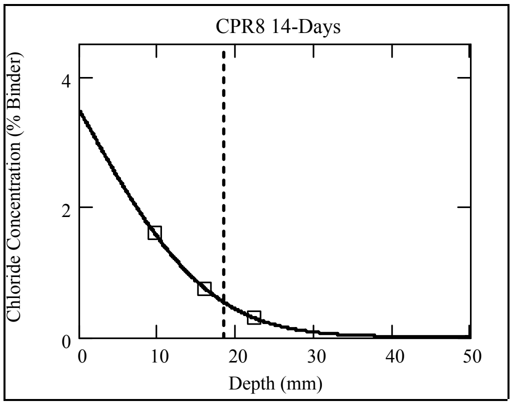
Diffusion(m^2/sec)	1.523E-11	**Background(% Bin)**	0.031
Surface(% Bin)	1.751	**R^2 Value**	0.996
Average Pene(mm)	14.580	**Derived % Cl(% Bin)**	0.626


CPR7 182-Days

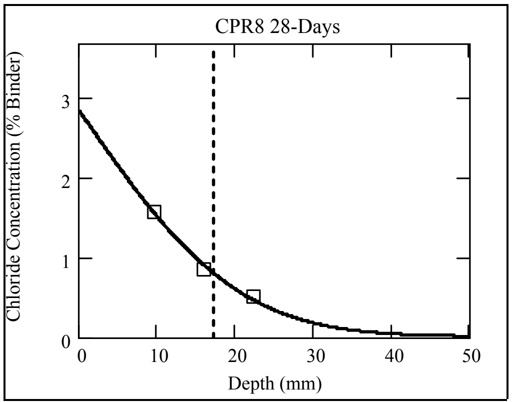
Diffusion(m^2/sec)	5.270E-12	**Background(% Bin)**	0.031
Surface(% Bin)	1.942	**R^2 Value**	0.987
Average Pene(mm)	11.151	**Derived % Cl(% Bin)**	0.769


CPR7 364-Days

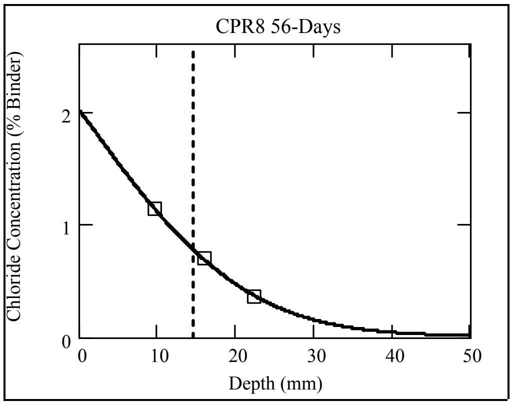
Diffusion(m^2/sec)	2.828E-12	**Background(% Bin)**	0.031
Surface(% Bin)	1.410	**R^2 Value**	0.998
Average Pene(mm)	10.439	**Derived % Cl(% Bin)**	0.629


CPR8 14-Days

Diffusion(m^2/sec)	6.825E-11	**Background(% Bin)**	0.013
Surface(% Bin)	3.485	**R^2 Value**	1.000
Average Pene(mm)	18.288	**Derived % Cl(% Bin)**	0.55

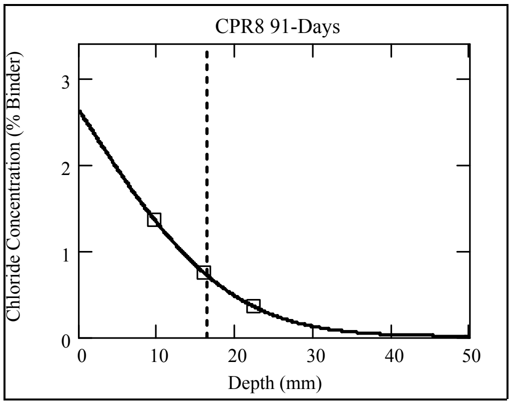

CPR8 28-Days

Diffusion(m^2/sec)	5.206E-11	**Background(% Bin)**	0.013
Surface(% Bin)	2.840	**R^2 Value**	0.995
Average Pene(mm)	17.018	**Derived % Cl(% Bin)**	0.815

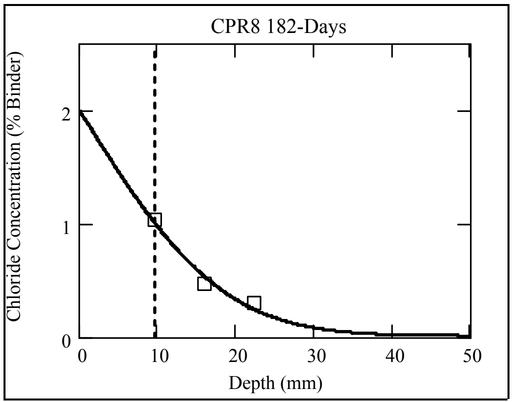

CPR8 56-Days

Diffusion(m^2/sec)	2.843E-11	**Background(% Bin)**	0.013
Surface(% Bin)	2.019	**R^2 Value**	1.000
Average Pene(mm)	14.427	**Derived % Cl(% Bin)**	0.784

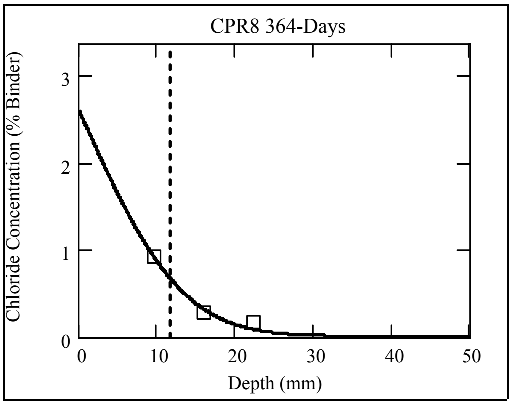
Elect. Tests 48. RMT Chloride Concentration by Binder Weight at AgNO3 Color-Change Boundary (CPR8 to CPR9 Mixtures).



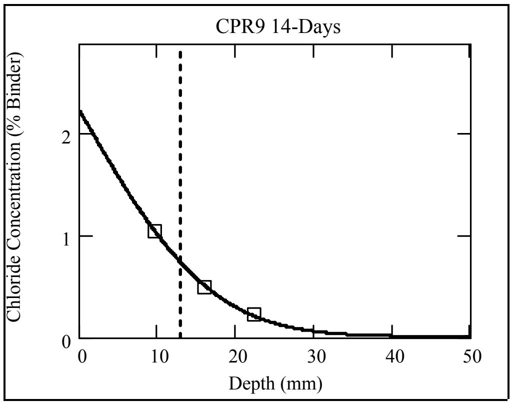
Diffusion(m^2/sec)	1.389E-11	**Background(% Bin)**	0.013
Surface(% Bin)	2.635	**R^2 Value**	1.000
Average Pene(mm)	16.307	**Derived % Cl(% Bin)**	0.72



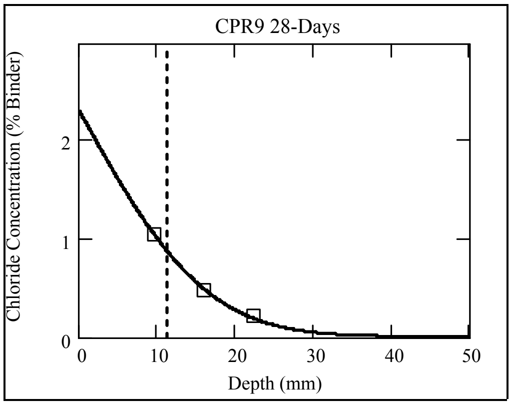
Diffusion(m^2/sec)	6.441E-12	**Background(% Bin)**	0.013
Surface(% Bin)	2.005	**R^2 Value**	0.987
Average Pene(mm)	9.500	**Derived % Cl(% Bin)**	1.018



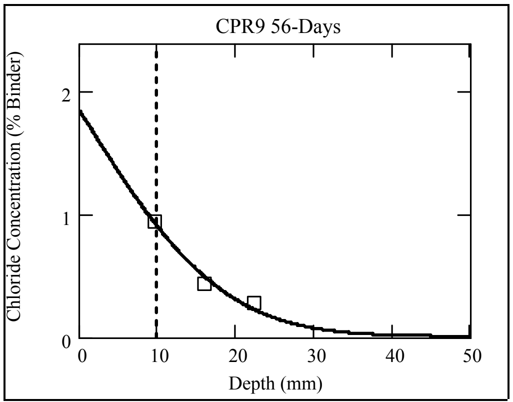
Diffusion(m^2/sec)	1.664E-12	**Background(% Bin)**	0.013
Surface(% Bin)	2.600	**R^2 Value**	0.990
Average Pene(mm)	11.608	**Derived % Cl(% Bin)**	0.677



Diffusion(m^2/sec)	7.160E-11	**Background(% Bin)**	0.010
Surface(% Bin)	2.219	**R^2 Value**	1.000
Average Pene(mm)	12.903	**Derived % Cl(% Bin)**	0.732

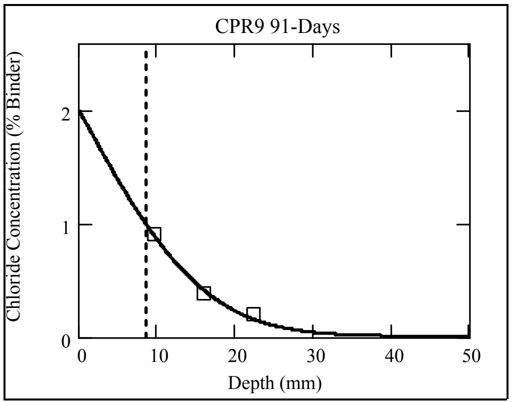


Diffusion(m^2/sec)	3.335E-11	**Background(% Bin)**	0.010
Surface(% Bin)	2.298	**R^2 Value**	0.998
Average Pene(mm)	11.227	**Derived % Cl(% Bin)**	0.872

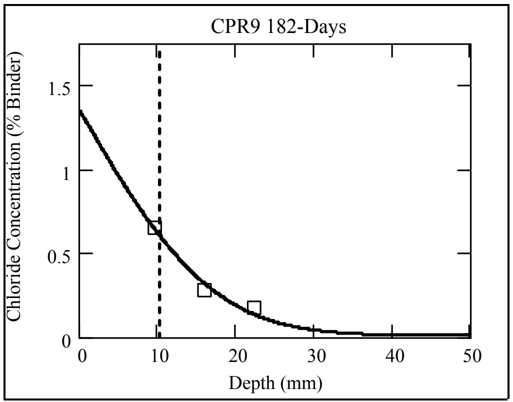


Diffusion(m^2/sec)	2.099E-11	**Background(% Bin)**	0.010
Surface(% Bin)	1.841	**R^2 Value**	0.989
Average Pene(mm)	9.703	**Derived % Cl(% Bin)**	0.918

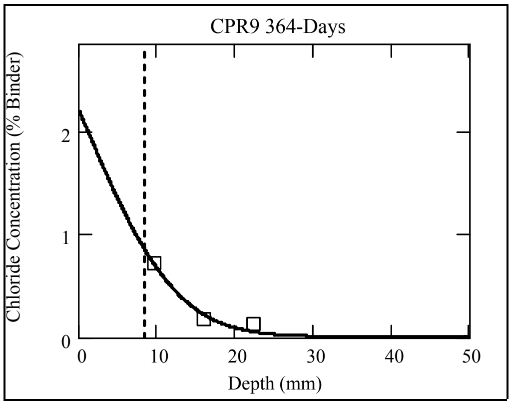
Elect. Tests 49. RMT Chloride Concentration by Binder Weight at AgNO3 Color-Change Boundary (CPR9 to CPR10 Mixtures).


CPR9 91-Days

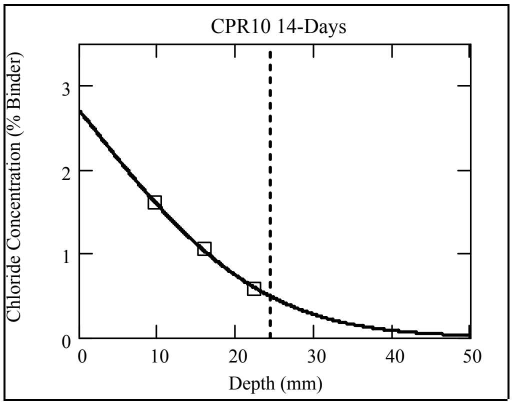
Diffusion(m^2/sec)	9.966E-12	**Background(% Bin)**	0.010
Surface(% Bin)	2.004	**R^2 Value**	0.995
Average Pene(mm)	8.560	**Derived % Cl(% Bin)**	0.995


CPR9 182-Days

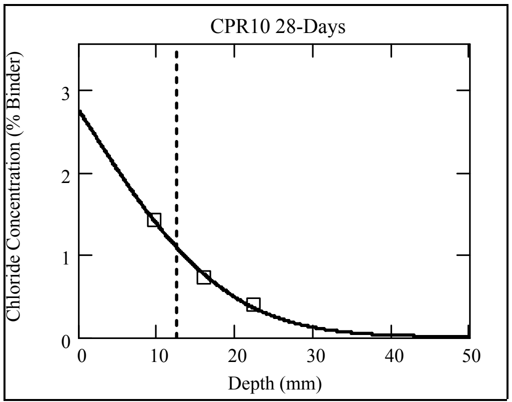
Diffusion(m^2/sec)	5.641E-12	**Background(% Bin)**	0.010
Surface(% Bin)	1.349	**R^2 Value**	0.987
Average Pene(mm)	10.236	**Derived % Cl(% Bin)**	0.602


CPR9 364-Days

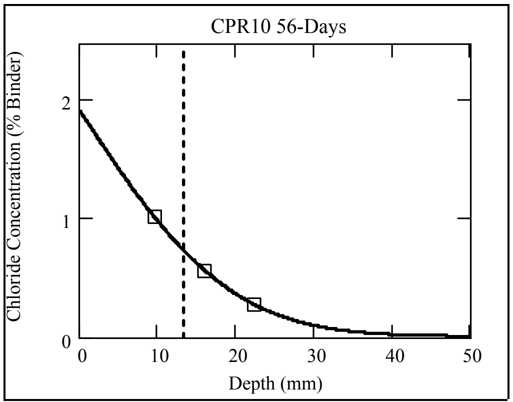
Diffusion(m^2/sec)	1.466E-12	**Background(% Bin)**	0.010
Surface(% Bin)	2.200	**R^2 Value**	0.984
Average Pene(mm)	8.357	**Derived % Cl(% Bin)**	0.851


CPR10 14-Days

Diffusion(m^2/sec)	1.356E-10	**Background(% Bin)**	0.010
Surface(% Bin)	2.698	**R^2 Value**	0.999
Average Pene(mm)	24.206	**Derived % Cl(% Bin)**	0.497

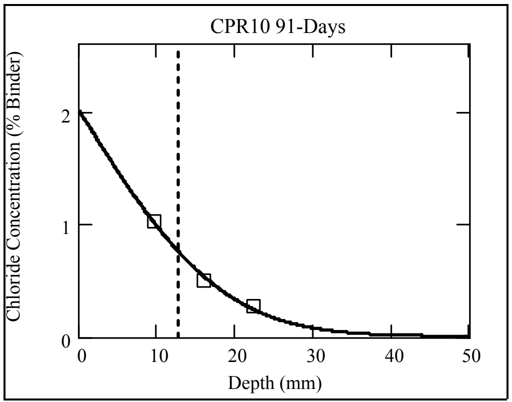

CPR10 28-Days

Diffusion(m^2/sec)	4.417E-11	**Background(% Bin)**	0.010
Surface(% Bin)	2.753	**R^2 Value**	0.997
Average Pene(mm)	12.370	**Derived % Cl(% Bin)**	1.1

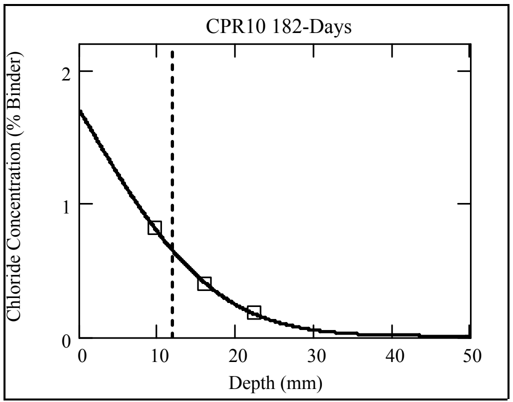

CPR10 56-Days

Diffusion(m^2/sec)	2.361E-11	**Background(% Bin)**	0.010
Surface(% Bin)	1.911	**R^2 Value**	1.000
Average Pene(mm)	13.157	**Derived % Cl(% Bin)**	0.74

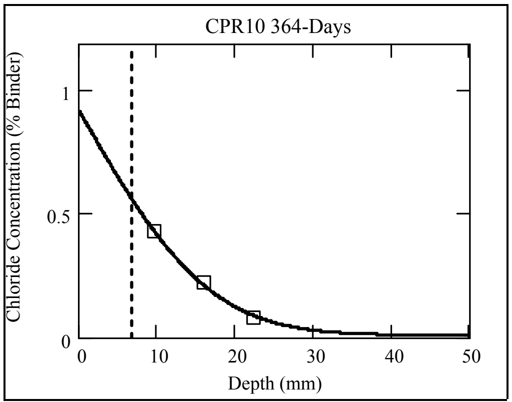
Elect. Tests 50. RMT Chloride Concentration by Binder Weight at AgNO3 Color-Change Boundary (CPR10 to CPR11 Mixtures).



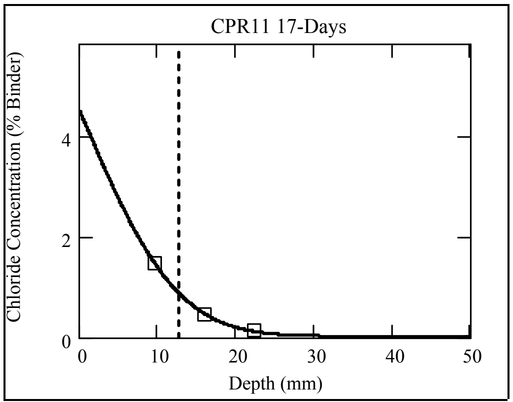
Diffusion(m^2/sec)	1.294E-11	**Background(% Bin)**	0.010
Surface(% Bin)	2.018	**R^2 Value**	0.997
Average Pene(mm)	12.573	**Derived % Cl(% Bin)**	0.769



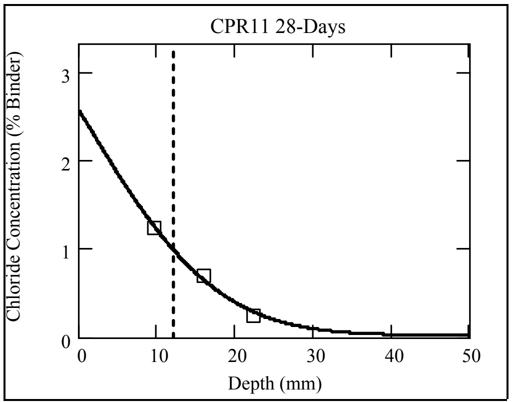
Diffusion(m^2/sec)	5.760E-12	**Background(% Bin)**	0.010
Surface(% Bin)	1.703	**R^2 Value**	1.000
Average Pene(mm)	11.786	**Derived % Cl(% Bin)**	0.655



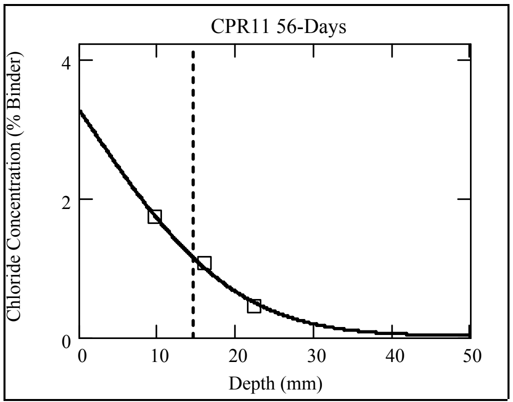
Diffusion(m^2/sec)	2.700E-12	**Background(% Bin)**	0.010
Surface(% Bin)	0.919	**R^2 Value**	0.999
Average Pene(mm)	6.655	**Derived % Cl(% Bin)**	0.564



Diffusion(m^2/sec)	3.191E-11	**Background(% Bin)**	0.025
Surface(% Bin)	4.505	**R^2 Value**	0.999
Average Pene(mm)	12.548	**Derived % Cl(% Bin)**	0.898

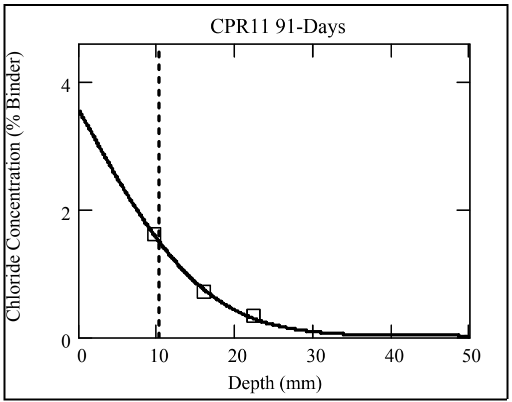


Diffusion(m^2/sec)	3.880E-11	**Background(% Bin)**	0.025
Surface(% Bin)	2.562	**R^2 Value**	0.996
Average Pene(mm)	11.963	**Derived % Cl(% Bin)**	0.995

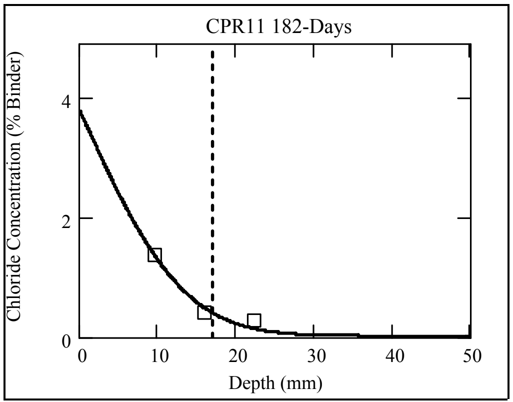


Diffusion(m^2/sec)	2.442E-11	**Background(% Bin)**	0.025
Surface(% Bin)	3.268	**R^2 Value**	0.995
Average Pene(mm)	14.529	**Derived % Cl(% Bin)**	1.142

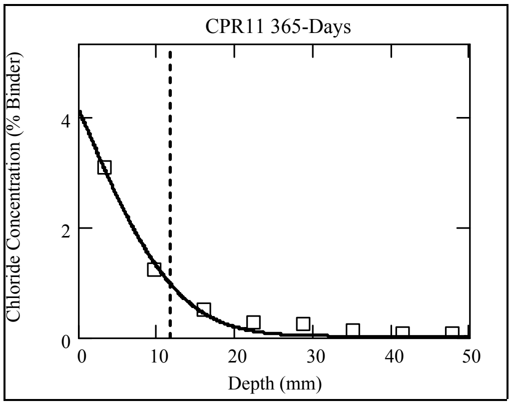
Elect. Tests 51. RMT Chloride Concentration by Binder Weight at AgNO3 Color-Change Boundary (CPR11 to CPR12 Mixtures).



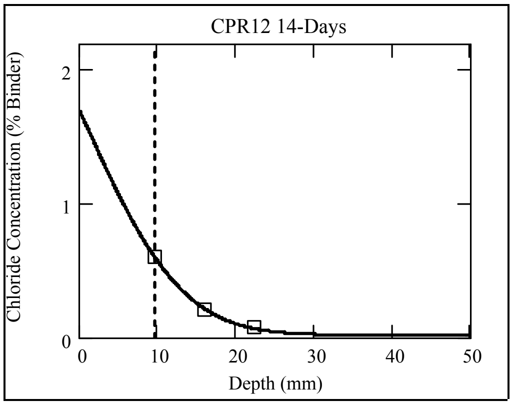
Diffusion(m^2/sec)	1.005E-11	**Background(% Bin)**	0.025
Surface(% Bin)	3.540	**R^2 Value**	0.998
Average Pene(mm)	10.058	**Derived % Cl(% Bin)**	1.514



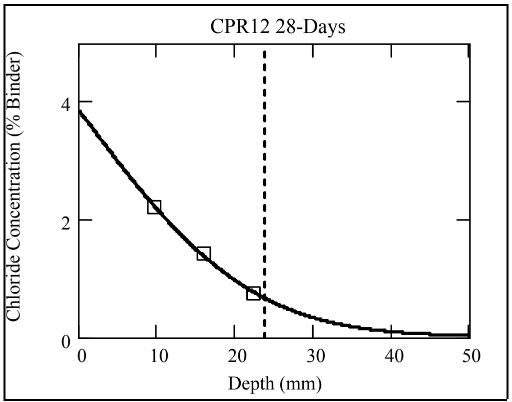
Diffusion(m^2/sec)	3.414E-12	**Background(% Bin)**	0.025
Surface(% Bin)	3.795	**R^2 Value**	0.983
Average Pene(mm)	16.967	**Derived % Cl(% Bin)**	0.407



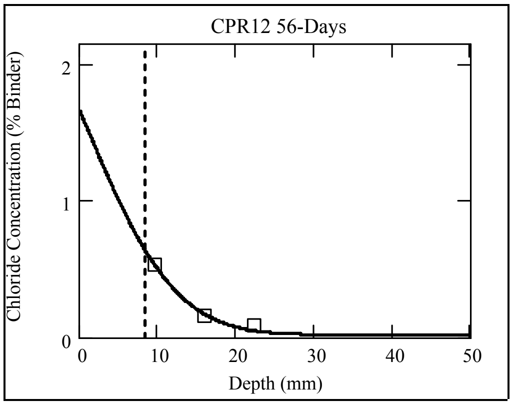
Diffusion(m^2/sec)	1.500E-12	**Background(% Bin)**	0.025
Surface(% Bin)	4.116	**R^2 Value**	0.996
Average Pene(mm)	11.659	**Derived % Cl(% Bin)**	0.968



Diffusion(m^2/sec)	4.274E-11	**Background(% Bin)**	0.019
Surface(% Bin)	1.695	**R^2 Value**	0.999
Average Pene(mm)	9.474	**Derived % Cl(% Bin)**	0.608

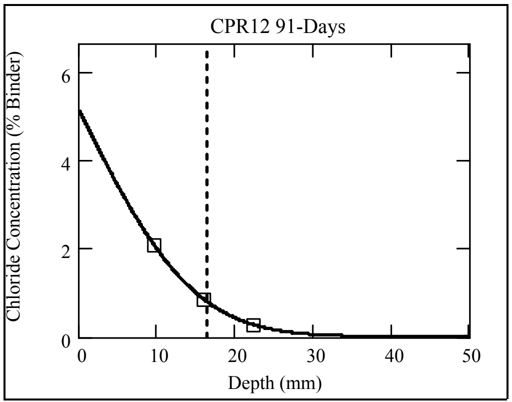


Diffusion(m^2/sec)	6.124E-11	**Background(% Bin)**	0.019
Surface(% Bin)	3.837	**R^2 Value**	0.999
Average Pene(mm)	23.673	**Derived % Cl(% Bin)**	0.664

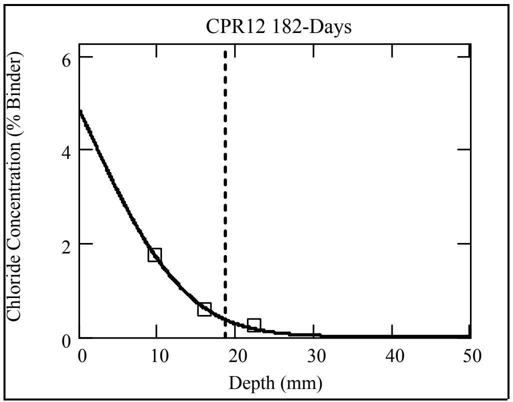


Diffusion(m^2/sec)	9.217E-12	**Background(% Bin)**	0.019
Surface(% Bin)	1.664	**R^2 Value**	0.995
Average Pene(mm)	8.357	**Derived % Cl(% Bin)**	0.638

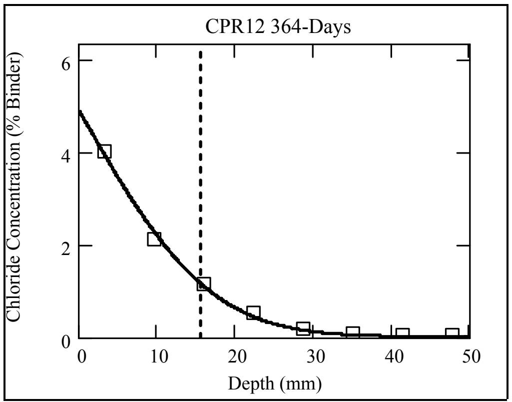
Elect. Tests 52. RMT Chloride Concentration by Binder Weight at AgNO3 Color-Change Boundary (CPR12 to CPR15 Mixtures).



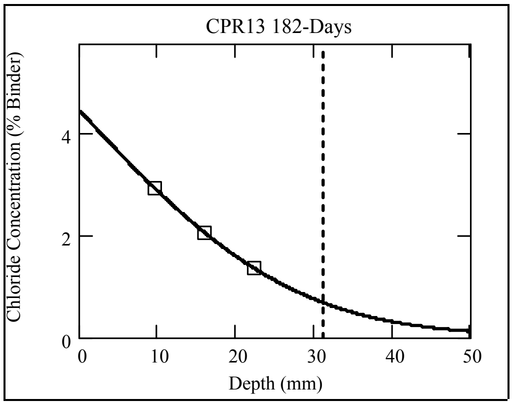
Diffusion(m^2/sec)	8.345E-12	**Background(% Bin)**	0.019
Surface(% Bin)	5.133	**R^2 Value**	1.000
Average Pene(mm)	16.332	**Derived % Cl(% Bin)**	0.806



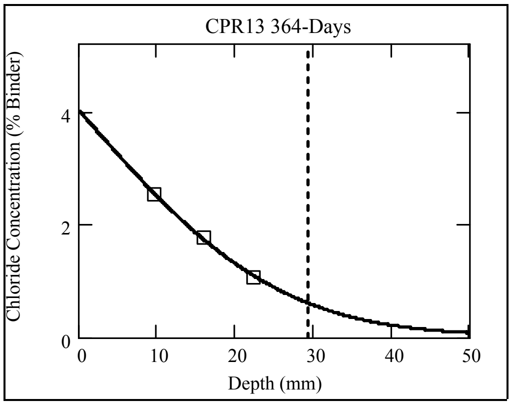
Diffusion(m^2/sec)	3.456E-12	**Background(% Bin)**	0.019
Surface(% Bin)	4.828	**R^2 Value**	0.997
Average Pene(mm)	18.567	**Derived % Cl(% Bin)**	0.379



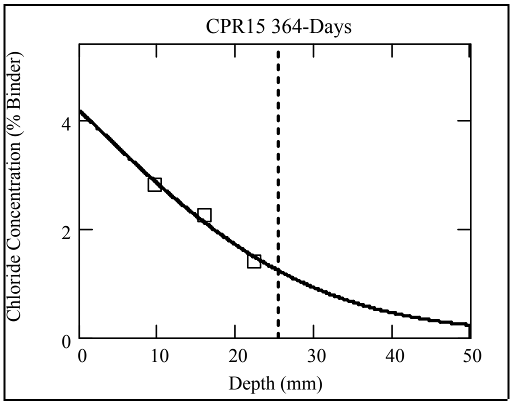
Diffusion(m^2/sec)	2.716E-12	**Background(% Bin)**	0.019
Surface(% Bin)	4.906	**R^2 Value**	0.999
Average Pene(mm)	15.392	**Derived % Cl(% Bin)**	1.186



Diffusion(m^2/sec)	1.473E-11	**Background(% Bin)**	0.031
Surface(% Bin)	4.429	**R^2 Value**	1.000
Average Pene(mm)	30.963	**Derived % Cl(% Bin)**	0.692

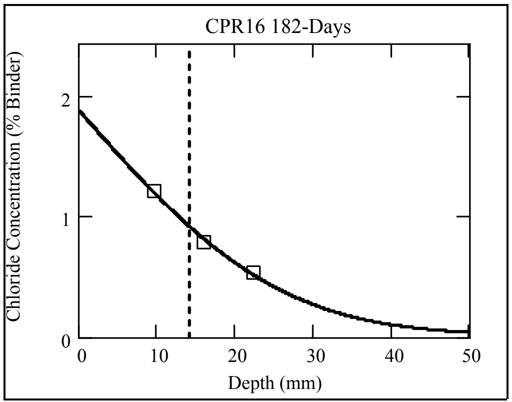


Diffusion(m^2/sec)	6.390E-12	**Background(% Bin)**	0.031
Surface(% Bin)	4.025	**R^2 Value**	0.999
Average Pene(mm)	29.159	**Derived % Cl(% Bin)**	0.614

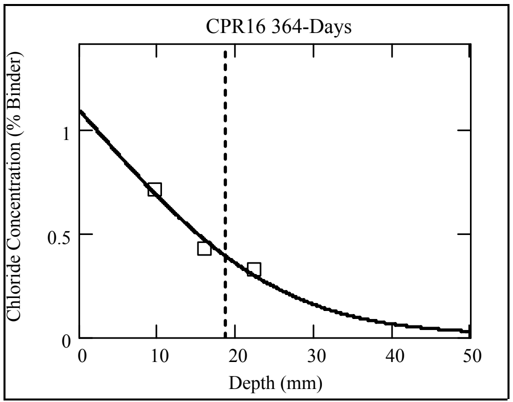


Diffusion(m^2/sec)	8.729E-12	**Background(% Bin)**	0.091
Surface(% Bin)	4.182	**R^2 Value**	0.985
Average Pene(mm)	25.375	**Derived % Cl(% Bin)**	1.232

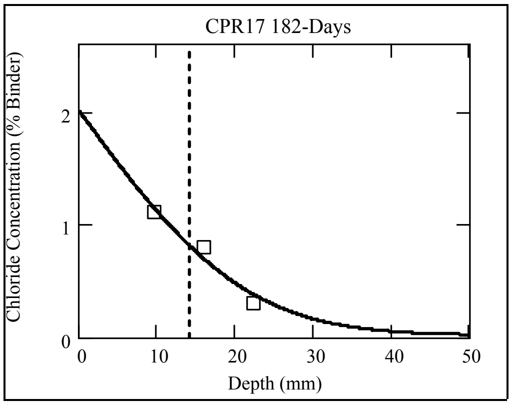
Elect. Tests 53. RMT Chloride Concentration by Binder Weight at AgNO3 Color-Change Boundary (CPR16 to CPR18 Mixtures).



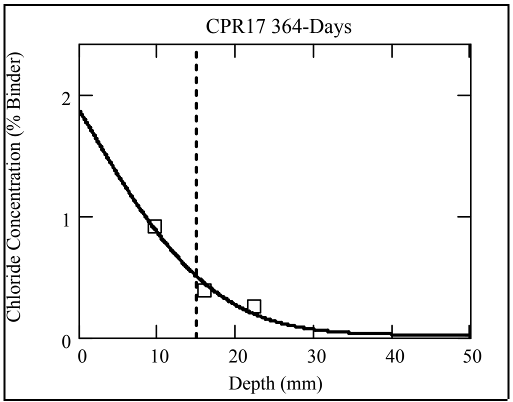
Diffusion(m^2/sec)	1.289E-11	**Background(% Bin)**	0.016
Surface(% Bin)	1.881	**R^2 Value**	0.996
Average Pene(mm)	14.021	**Derived % Cl(% Bin)**	0.923



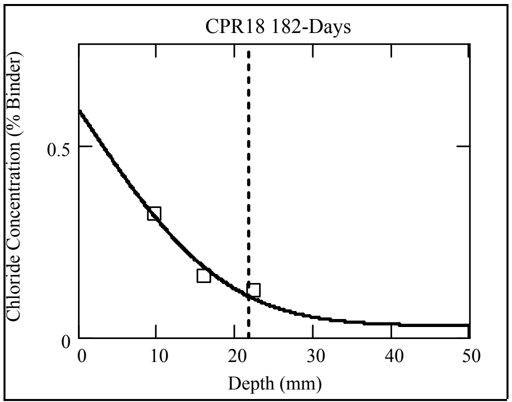
Diffusion(m^2/sec)	6.271E-12	**Background(% Bin)**	0.016
Surface(% Bin)	1.095	**R^2 Value**	0.981
Average Pene(mm)	18.567	**Derived % Cl(% Bin)**	0.393



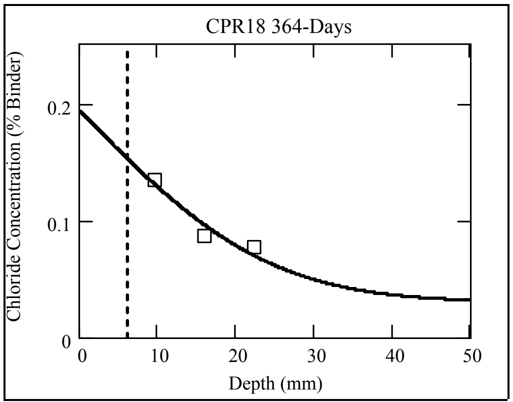
Diffusion(m^2/sec)	8.847E-12	**Background(% Bin)**	0.021
Surface(% Bin)	2.017	**R^2 Value**	0.971
Average Pene(mm)	14.021	**Derived % Cl(% Bin)**	0.821



Diffusion(m^2/sec)	2.806E-12	**Background(% Bin)**	0.021
Surface(% Bin)	1.870	**R^2 Value**	0.987
Average Pene(mm)	14.808	**Derived % Cl(% Bin)**	0.511

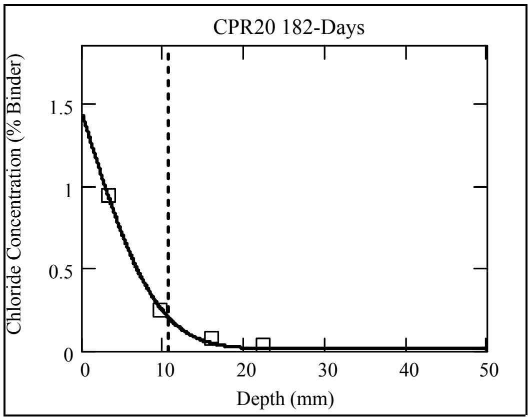


Diffusion(m^2/sec)	6.712E-12	**Background(% Bin)**	0.031
Surface(% Bin)	0.593	**R^2 Value**	0.976
Average Pene(mm)	21.565	**Derived % Cl(% Bin)**	0.108

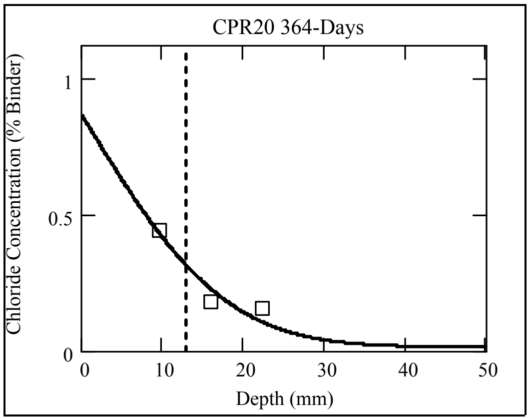


Diffusion(m^2/sec)	5.751E-12	**Background(% Bin)**	0.031
Surface(% Bin)	0.195	**R^2 Value**	0.956
Average Pene(mm)	6.071	**Derived % Cl(% Bin)**	0.154

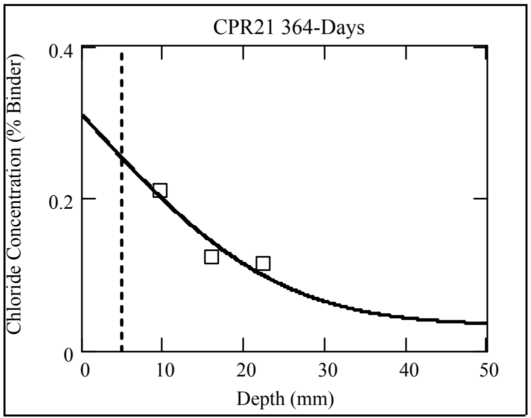
Elect. Tests 54. RMT Chloride Concentration by Binder Weight at AgNO3 Color-Change Boundary (CPR20 to CPR21 Mixtures).



Diffusion(m^2/sec)	1.587E-12	**Background(% Bin)**	0.012
Surface(% Bin)	1.432	**R^2 Value**	0.999
Average Pene(mm)	10.541	**Derived % Cl(% Bin)**	0.205



Diffusion(m^2/sec)	3.039E-12	**Background(% Bin)**	0.014
Surface(% Bin)	0.865	**R^2 Value**	0.956
Average Pene(mm)	12.776	**Derived % Cl(% Bin)**	0.317



Diffusion(m^2/sec)	5.638E-12	**Background(% Bin)**	0.034
Surface(% Bin)	0.310	**R^2 Value**	0.939
Average Pene(mm)	4.877	**Derived % Cl(% Bin)**	0.253

Elect. Tests 55. RMT Diffusion Coefficients (CPR1 to CPR7 Mixtures).

MIX	Testing (Days)	Aveg. Penet. (mm)	Temp. Ave. (K)	Applied Volt. (V)	Test Duration (sec)	α	Diffusion Coeff. (m^2/sec)
CPR1	14	-	298.65	10	64800	0.0315	-
	28	-	298.15	10	64800	0.0315	-
	56	-	297.65	30	64800	0.0168	-
	91	-	297.48	30	64800	0.0168	-
	182	38.142	297.98	30	64800	0.0168	2.506E-11
	364	31.855	296.65	30	64800	0.0168	2.066E-11
CPR2	14	-	297.65	30	64800	0.0168	-
	28	-	298.15	30	64800	0.0168	-
	56	-	296.32	30	64800	0.0168	-
	91	-	297.15	30	64800	0.0168	-
	182	12.182	296.65	30	64800	0.0168	7.393E-12
	364	14.178	296.65	30	64800	0.0168	8.717E-12
CPR3	14	-	297.82	10	64800	0.0315	-
	28	-	297.98	10	64800	0.0315	-
	56	-	297.48	10	64800	0.0314	-
	91	11.378	295.32	10	64800	0.0313	2.004E-11
	182	8.740	298.15	10	64800	0.0315	1.460E-11
	364	26.994	298.15	30	64800	0.0168	1.743E-11
CPR4	14	-	299.32	60	64800	0.0117	-
	28	-	297.98	60	64800	0.0117	-
	56	-	293.98	60	64800	0.0116	-
	91	4.648	295.32	60	64800	0.0116	1.326E-12
	182	8.787	298.15	60	64800	0.0117	2.671E-12
	364	5.630	298.15	60	64800	0.0117	1.651E-12
CPR5	14	-	297.98	10	64800	0.0315	-
	28	-	297.48	30	64800	0.0168	-
	56	-	292.82	60	64800	0.0116	-
	91	19.260	296.32	60	64800	0.0117	6.089E-12
	182	12.378	298.65	60	64800	0.0117	3.853E-12
	364	8.348	298.65	60	64800	0.0117	2.532E-12
CPR6	14	15.309	295.98	10	64800	0.0314	2.856E-11
	28	13.389	296.15	10	64800	0.0314	2.440E-11
	56	23.966	297.98	30	64800	0.0168	1.536E-11
	91	17.663	297.32	30	64800	0.0168	1.107E-11
	182	23.104	296.82	60	64800	0.0117	7.375E-12
	364	22.336	296.82	60	64800	0.0117	7.119E-12
CPR7	14	17.834	298.48	60	64800	0.0117	5.657E-12
	28	8.421	297.48	60	64800	0.0117	2.546E-12
	56	9.336	297.98	60	64800	0.0117	2.848E-12
	91	14.575	298.32	60	64800	0.0117	4.574E-12
	182	11.160	296.82	60	64800	0.0117	3.432E-12
	364	10.444	296.32	60	64800	0.0117	3.194E-12

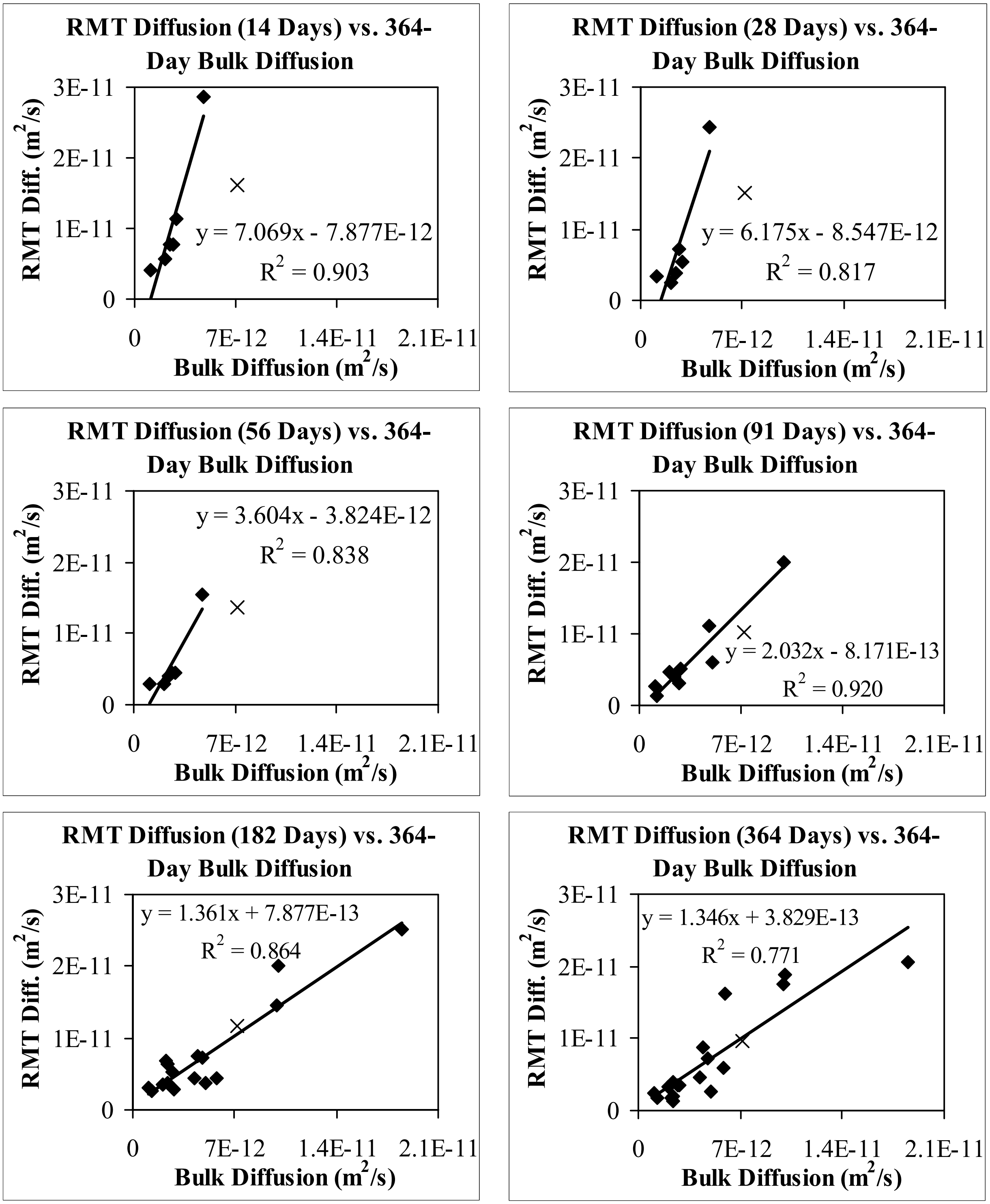
Elect. Tests 56. RMT Diffusion Coefficients (CPR8 to CPR15 Mixtures).

MIX	Testing (Days)	Aveg. Penet. (mm)	Temp. Ave. (K)	Applied Volt. (V)	Test Duration (sec)	α	Diffusion Coeff. (m^2/sec)
CPR8	14	18.299	296.48	30	64800	0.0168	1.147E-11
	28	17.013	295.98	60	64800	0.0116	5.341E-12
	56	14.416	298.82	60	64800	0.0117	4.528E-12
	91	16.310	299.15	60	64800	0.0117	5.162E-12
	182	9.509	296.65	60	64800	0.0117	2.893E-12
	364	11.602	297.15	60	64800	0.0117	3.580E-12
CPR9	14	12.900	296.15	60	64800	0.0117	3.993E-12
	28	11.227	298.48	60	64800	0.0117	3.472E-12
	56	9.704	297.65	60	64800	0.0117	2.965E-12
	91	8.560	297.82	60	64800	0.0117	2.594E-12
	182	10.229	295.48	60	64800	0.0116	3.115E-12
	364	8.352	295.48	60	64800	0.0116	2.508E-12
CPR10	14	24.210	296.98	60	64800	0.0117	7.747E-12
	28	12.366	297.98	60	64800	0.0117	3.841E-12
	56	13.150	296.65	60	64800	0.0117	4.082E-12
	91	12.583	298.65	60	64800	0.0117	3.920E-12
	182	11.774	297.65	60	64800	0.0117	3.642E-12
	364	6.649	297.65	60	64800	0.0117	1.975E-12
CPR11	14	12.535	299.32	30	64800	0.0169	7.689E-12
	28	11.961	298.15	30	64800	0.0168	7.280E-12
	56	14.520	298.48	60	64800	0.0117	4.558E-12
	91	10.050	298.15	60	64800	0.0117	3.083E-12
	182	16.967	298.15	60	64800	0.0117	5.363E-12
	364	11.648	298.15	60	64800	0.0117	3.607E-12
CPR12	14	9.483	296.48	10	64800	0.0314	1.609E-11
	28	23.674	297.65	30	64800	0.0168	1.514E-11
	56	8.352	296.98	10	64800	0.0314	1.374E-11
	91	16.331	295.82	30	64800	0.0168	1.013E-11
	182	18.575	296.82	30	64800	0.0168	1.166E-11
	364	15.397	296.65	30	64800	0.0168	9.530E-12
CPR13	14	-	297.48	10	64800	0.0314	-
	28	-	295.98	10	64800	0.0314	-
	56	-	299.15	30	64800	0.0169	-
	91	-	297.65	30	64800	0.0168	-
	182	30.950	296.32	30	64800	0.0168	2.002E-11
	364	29.158	296.98	30	64800	0.0168	1.884E-11
CPR15	14	-	296.98	10	64800	0.0314	-
	28	-	296.32	10	64800	0.0314	-
	56	-	298.32	30	64800	0.0168	-
	91	-	298.98	30	64800	0.0168	-
	182	-	296.48	30	64800	0.0168	-
	364	25.364	296.65	30	64800	0.0168	1.624E-11

Elect. Tests 57. RMT Diffusion Coefficients (CPR1 to CPR7 Mixtures).

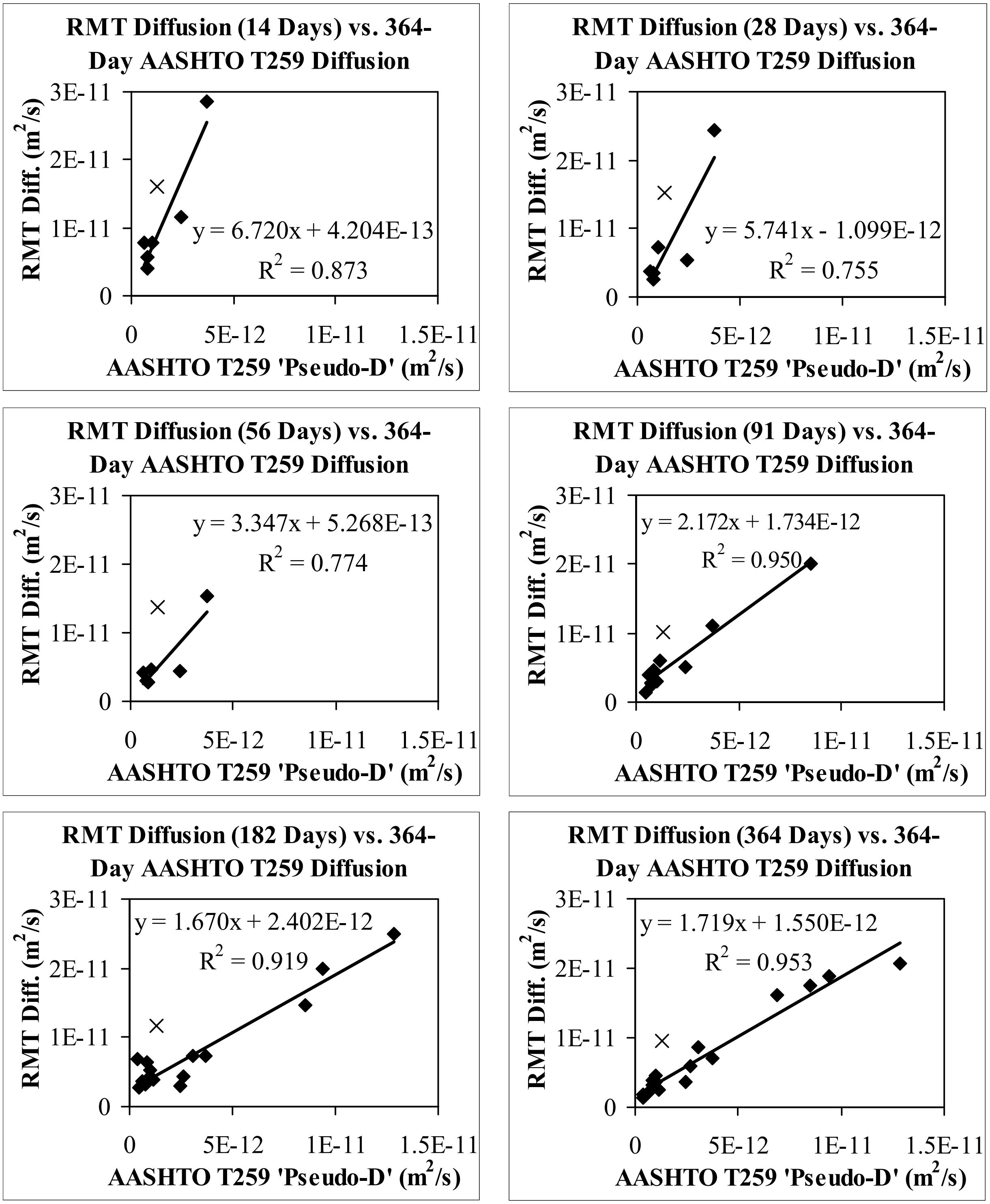
MIX	Testing (Days)	Aveg. Penet. (mm)	Temp. Ave. (K)	Applied Volt. (V)	Test Duration (sec)	α	Diffusion Coeff. (m^2/sec)
CPR16	14	-	296.82	10	64800	0.0314	-
	28	-	296.15	10	64800	0.0314	-
	56	-	298.82	30	64800	0.0168	-
	91	-	298.48	30	64800	0.0168	-
	182	14.028	297.15	60	64800	0.0117	4.377E-12
	364	18.559	296.82	60	64800	0.0117	5.867E-12
CPR17	14	-	296.82	10	64800	0.0314	-
	28	-	297.32	30	64800	0.0168	-
	56	-	297.65	30	64800	0.0168	-
	91	-	299.48	60	64800	0.0117	-
	182	14.028	296.98	60	64800	0.0117	4.374E-12
	364	14.814	296.65	60	64800	0.0117	4.628E-12
CPR18	14	-	296.48	10	64800	0.0314	-
	28	-	297.15	30	64800	0.0168	-
	56	-	298.15	60	64800	0.0117	-
	91	-	299.15	60	64800	0.0117	-
	182	21.562	295.98	60	64800	0.0116	6.844E-12
	364	6.080	294.98	60	64800	0.0116	1.778E-12
CPR20	14	-	297.32	10	64800	0.0314	-
	28	-	296.98	30	64800	0.0168	-
	56	-	298.32	60	64800	0.0117	-
	91	-	299.15	60	64800	0.0117	-
	182	10.547	296.15	30	64800	0.0168	6.306E-12
	364	12.787	295.65	60	64800	0.0116	3.950E-12
CPR21	14	-	296.65	10	64800	0.0314	-
	28	-	297.65	30	64800	0.0168	-
	56	-	297.65	30	64800	0.0168	-
	91	-	299.48	60	64800	0.0117	-
	182	-	296.65	60	64800	0.0117	-
	364	4.885	295.65	60	64800	0.0116	1.402E-12

Elect. Tests 58. RMT Diffusion Coefficients vs. 364-Day Bulk Diffusion Coefficients.



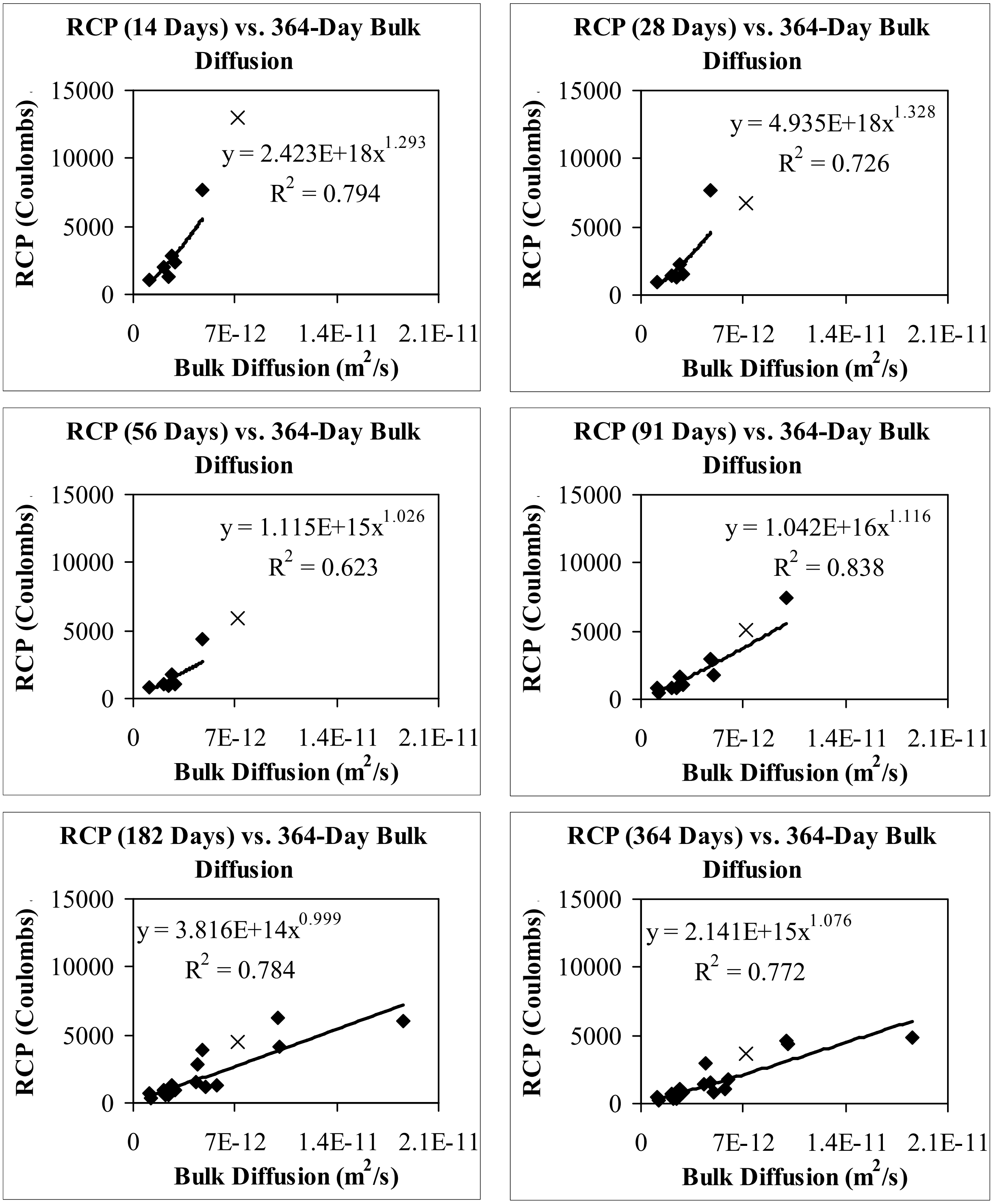
× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

Elect. Tests 59. RMT Diffusion Coefficients vs. 364-Day AASHTO T259 Pseudo-Diffusion Coefficients.



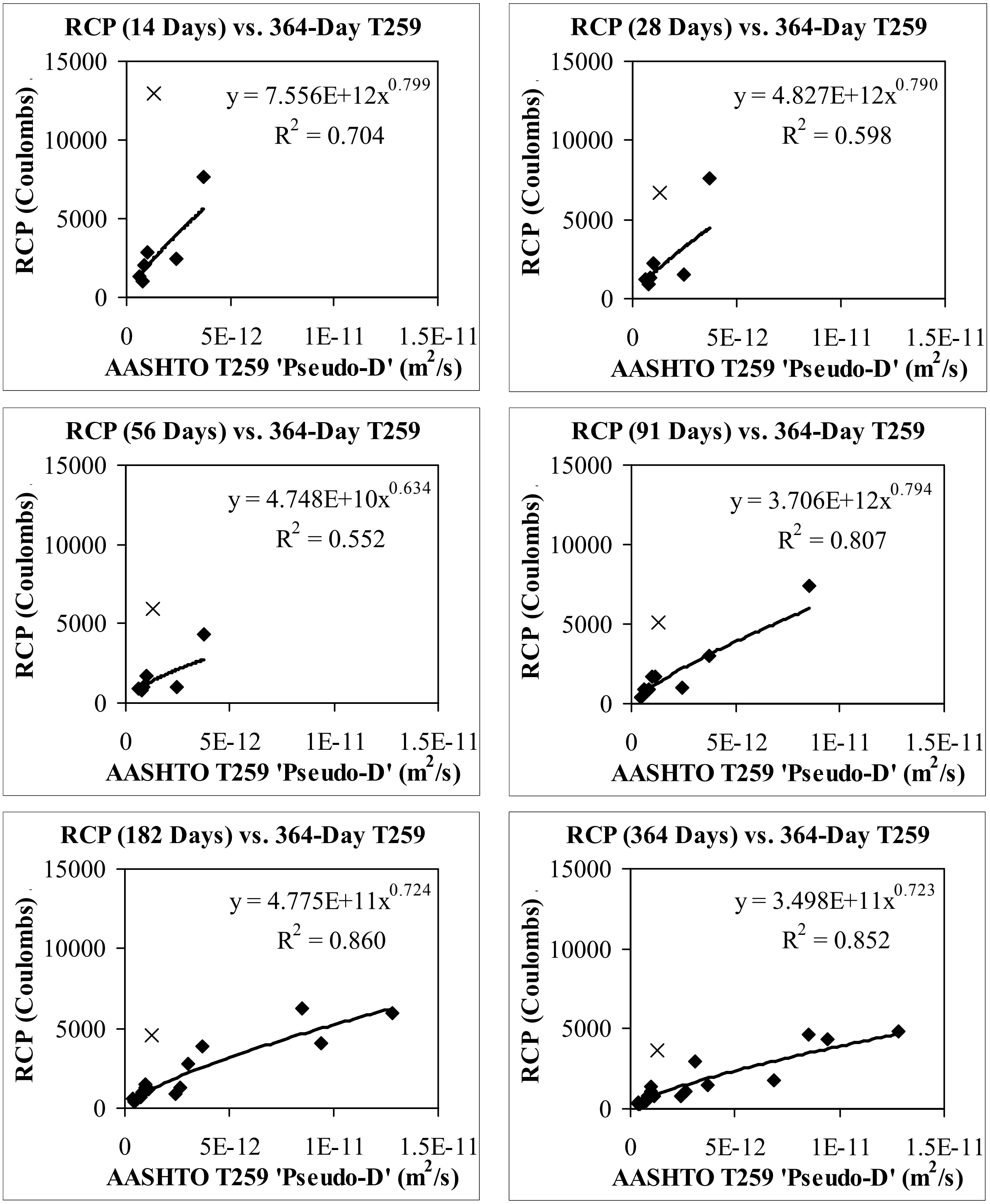
× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

Elect. Tests 60. RCP Coulombs vs. 364-Day Bulk Diffusion (Only Mixtures that RMT Results were Available).



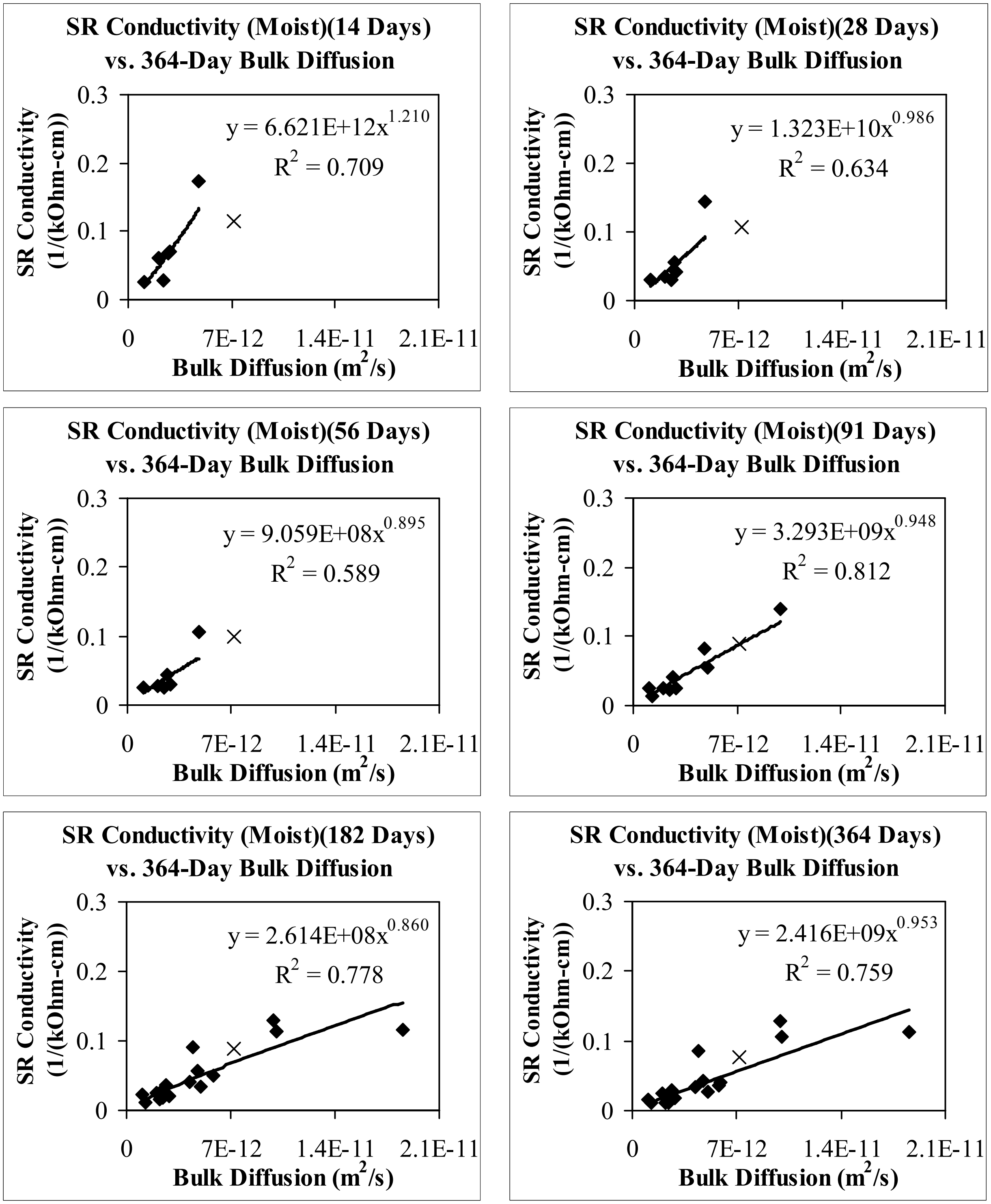
× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

Elect. Tests 61. RCP Coulombs vs. 364-Day AASHTO T259 Pseudo-Diffusion Coefficients (Only Mixtures that RMT Results were Available).



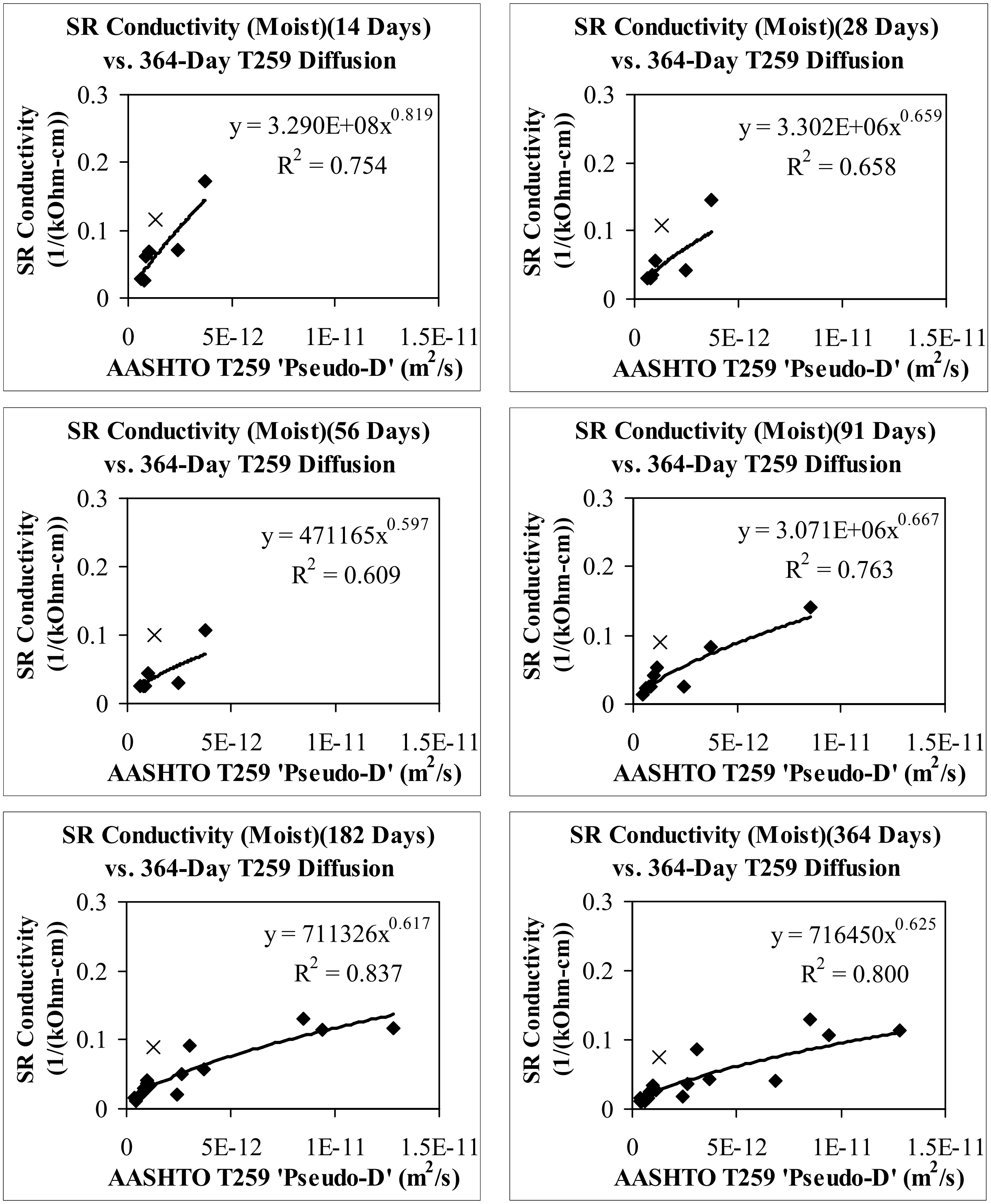
× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

Elect. Tests 62. SR (Moist Cured) vs. 364-Day Bulk Diffusion (Only Mixtures that RMT Results were Available).



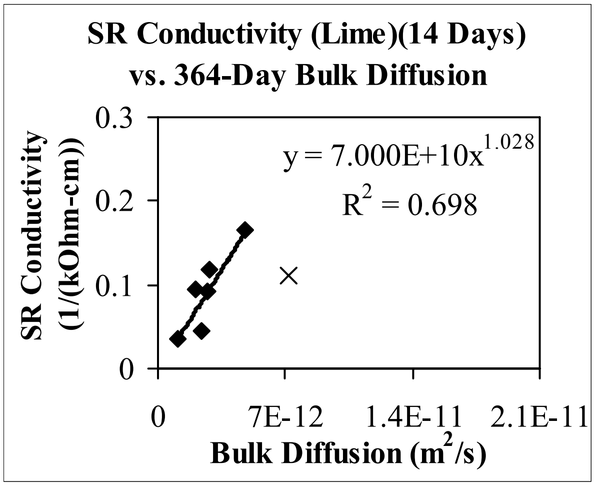
× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

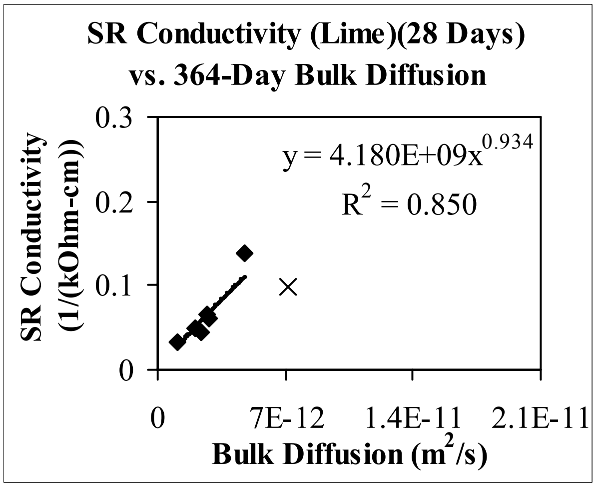
Elect. Tests 63. SR (Moist Cured) vs. 364-Day AASHTO T259 Pseudo-Diffusion Coefficients (Only Mixtures that RMT Results were Available).

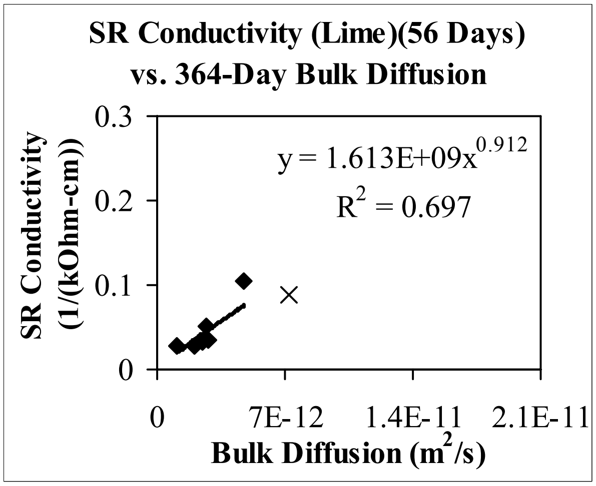


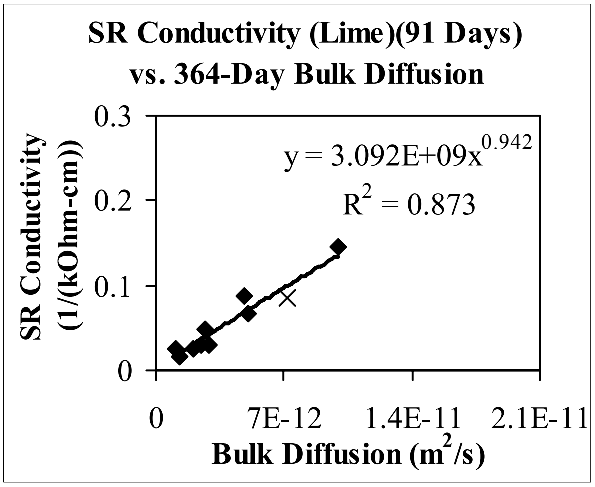
× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

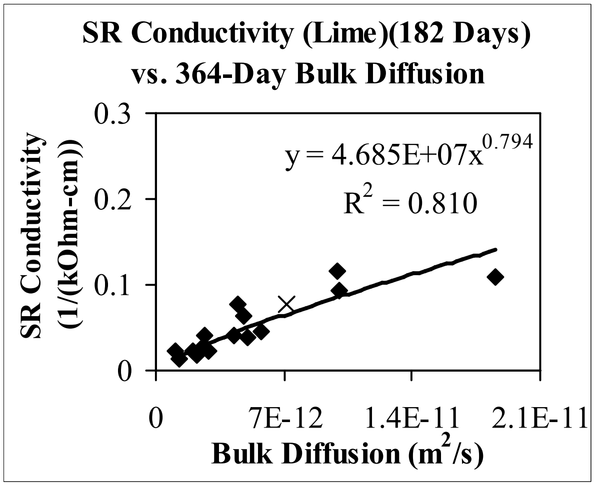
Elect. Tests 64. SR (Lime Cured) vs. 364-Day Bulk Diffusion (Only Mixtures that RMT Results were Available).

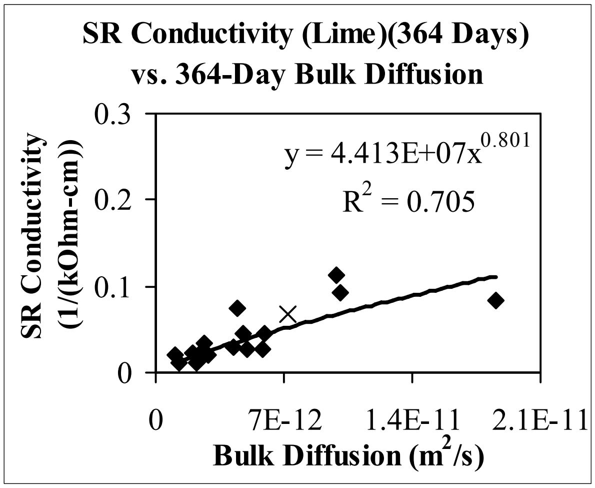

SR Conductivity (Lime)(14 Days) vs. 364-Day Bulk Diffusion


SR Conductivity (Lime)(28 Days) vs. 364-Day Bulk Diffusion


SR Conductivity (Lime)(56 Days) vs. 364-Day Bulk Diffusion

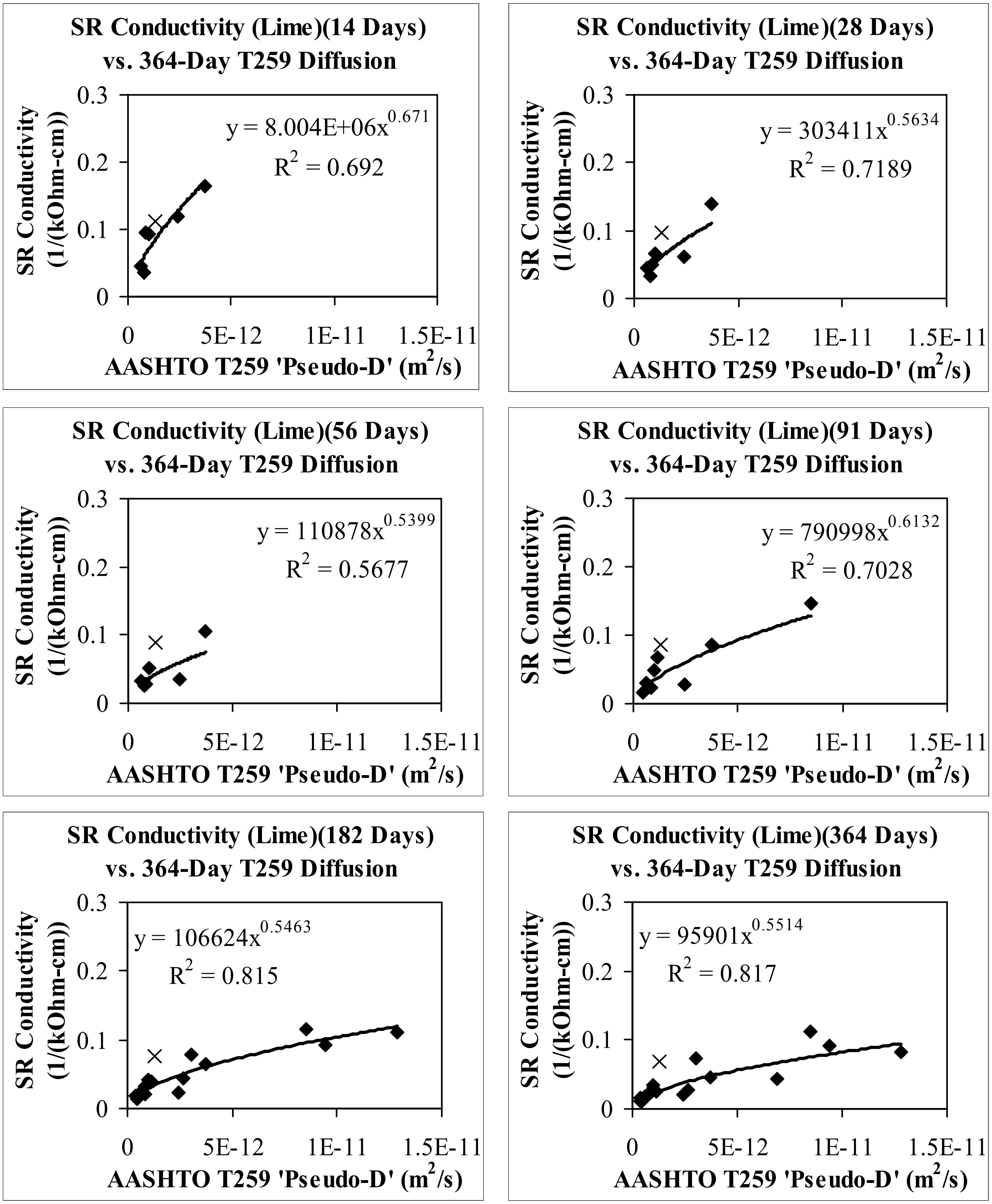

SR Conductivity (Lime)(91 Days) vs. 364-Day Bulk Diffusion


SR Conductivity (Lime)(182 Days) vs. 364-Day Bulk Diffusion


SR Conductivity (Lime)(364 Days) vs. 364-Day Bulk Diffusion

× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

Elect. Tests 65. SR (Lime Cured) vs. 364-Day AASHTO T259 Pseudo-Diffusion Coefficients (Only Mixtures that RMT Results were Available).



× Concrete mixture containing Calcium Nitrate (CPR12). It was not include in the general correlation calculations.

APPENDIX D

FIELD CORE SAMPLING ANALYSIS RESULTS.

Appendix Table of Contents

Field Tests 1. Initial Chloride Background Level of Cored Samples

Bridge Name	**Lab. #**	**Initial Chloride Samples (lb/yd^3)**			
		A	**B**	**C**	**Average**
Hurricane Pass (HPB)	**5016**	-	-	-	0.547[(a)]
	5017	0.515	0.514	0.570	0.533
	5018	0.529	0.594	0.560	0.561
Broadway Replacement (BRB)	**5054**	0.426	0.483	0.492	0.467
	5081	0.843	0.904	0.828	0.858[(b)]
Seabreeze West Bound (SWB)	**5082**	0.435	0.508	0.458	0.467
	5083	0.390	0.441	0.465	0.432
Granada (GRB)	**5084**	0.669	0.649	0.594	0.637
Turkey Creek (TCB)	**5078**	0.550	0.574	0.544	0.556
	5079	0.423	0.420	0.427	0.423
	5080	0.414	0.415	0.423	0.417
New Roosevelt (NRB)	**5075**	0.623	0.609	0.609	0.614
	5076	0.445	0.423	0.427	0.432
	5077	0.332	0.407	0.408	0.382

(a) Initial Chlorides were not tested for this sample. An average between Lab sample# 5017 and 5018 was reported.

(b) Initial Chloride value was considered an erroneous value (too high). The value of initial chlorides from Lab sample# 5054 was used.

Field Tests 2. Chloride Profile Testing Results of Cored Samples.

Bridge Hurricane (HPB)
Lab # 5016

Depth	NaCl (lb/yd^3)			
(mm)	A	B	C	AVG
3.18	13.327	13.285	13.452	13.355
9.53	3.110	3.512	3.555	3.392
15.88	2.155	2.201	2.176	2.177
22.23	0.677	0.688	0.687	0.684
28.58	0.564	0.490	0.495	0.516
34.93	0.440	0.441	0.422	0.434
41.28	0.357	0.341	0.349	0.349
47.63	0.373	0.435	0.360	0.389
53.98	0.349	0.350	0.345	0.348

Bridge Hurricane (HPB)
Lab # 5017

Depth	NaCl (lb/yd^3)			
(mm)	A	B	C	AVG
1.00	32.329	32.186	31.936	32.150
3.00	33.485	33.629	32.969	33.361
5.00	26.499	26.952	26.844	26.765
7.00	22.561	22.301	22.305	22.389
9.00	20.412	20.575	20.585	20.524
11.00	15.275	15.260	15.259	15.265
15.18	7.910	8.005	8.149	8.021
21.53	2.766	2.737	2.774	2.759
27.88	0.773	0.795	0.802	0.790
34.23	0.317	0.366	0.359	0.347

Bridge Hurricane (HPB)
Lab # 5018

Depth	NaCl (lb/yd^3)			
(mm)	A	B	C	AVG
1.00	37.618	37.627	38.201	37.815
3.00	34.599	34.440	34.804	34.614
5.00	30.440	30.431	30.556	30.476
7.00	25.696	25.936	26.046	25.893
9.00	22.942	23.073	22.980	22.998
11.00	19.042	17.179	17.252	17.824
15.18	7.728	8.263	7.944	7.978
21.53	1.744	1.772	1.783	1.766
27.88	0.454	0.504	0.469	0.476
34.23	0.592	0.603	0.548	0.581

Bridge Broadway Replacement (BRB)
Lab # 5054

Depth	NaCl (lb/yd^3)			
(mm)	A	B	C	AVG
1.00	20.128	20.785	20.920	20.611
3.00	26.407	25.674	26.311	26.131
5.00	23.063	22.699	22.624	22.795
7.00	19.445	20.026	19.302	19.591
9.00	19.561	19.906	19.906	19.791
11.00	16.881	16.904	17.254	17.013
15.18	7.497	8.001	7.857	7.785
21.53	1.175	1.222	1.217	1.205
27.88	0.553	0.589	0.596	0.579
34.23	0.453	0.475	0.501	0.476

Bridge Broadway Replacement (BRB)
Lab # 5081

Depth	NaCl (lb/yd^3)			
(mm)	A	B	C	AVG
1.00	30.614	30.399	30.521	30.511
3.00	24.608	24.693	24.628	24.643
5.00	20.438	20.166	19.773	20.126
7.00	16.360	16.016	15.949	16.108
9.00	14.177	13.895	14.079	14.050
11.00	12.665	12.318	12.657	12.547
15.18	3.649	3.711	3.586	3.649
21.53	0.248	0.264	0.236	0.249
27.88	0.252	0.265	0.268	0.262
34.23	0.288	0.300	0.266	0.285

Bridge Seabreeze (SWB)
Lab # 5082

Depth	NaCl (lb/yd^3)			
(mm)	A	B	C	AVG
1.00	40.658	40.645	40.062	40.455
3.00	38.187	37.863	38.175	38.075
5.00	31.937	31.980	31.836	31.918
7.00	29.026	28.978	29.297	29.100
9.00	27.541	27.760	27.114	27.472
11.00	26.470	26.290	26.278	26.346
15.18	20.980	20.701	20.330	20.670
21.53	7.624	7.376	8.123	7.708
27.88	-	-	-	-
34.23	-	-	-	-

Field Tests 3. Chloride Profile Testing Results of Cored Samples (Cont.).

Bridge Seabreeze (SWB)
Lab # 5083

Depth	NaCl (lb/yd^3)			
(mm)	A	B	C	AVG
1.00	39.841	39.841	39.868	39.850
3.00	38.948	39.148	38.488	38.861
5.00	34.426	35.015	34.545	34.662
7.00	32.315	32.972	32.720	32.669
9.00	26.697	26.801	27.009	26.836
11.00	22.871	23.330	23.327	23.176
15.18	13.869	14.011	14.201	14.027
21.53	1.623	1.990	2.382	1.998
27.88	0.459	0.459	0.436	0.451
34.23	0.466	0.495	0.452	0.471

Bridge Granada Crashwall (GRB)
Lab # 5084

Depth	NaCl (lb/yd^3)			
(mm)	A	B	C	AVG
1.00	0.918	0.869	0.858	0.882
3.00	0.671	0.676	0.694	0.680
5.00	0.560	0.595	0.616	0.590
7.00	0.478	0.501	0.490	0.490
9.00	0.450	0.472	0.484	0.469
11.00	0.504	0.443	0.437	0.461
15.18	0.445	0.459	0.408	0.437
21.53	0.385	0.402	0.381	0.389
27.88	0.453	0.398	0.377	0.409
34.23	0.354	0.397	0.404	0.385

Bridge Turkey Creek (TCB)
Lab # 5078

Depth	NaCl (lb/yd^3)			
(mm)	A	B	C	AVG
1.00	26.038	25.618	25.965	25.874
3.00	19.101	19.205	19.277	19.194
5.00	14.341	14.275	14.242	14.286
7.00	11.838	12.028	11.490	11.785
9.00	9.381	9.381	9.303	9.355
11.00	6.469	6.447	6.363	6.426
15.18	4.410	4.328	4.338	4.359
21.53	1.605	1.616	1.599	1.607
27.88	2.257	-	-	2.257
34.23	0.770	0.816	0.743	0.776

Bridge Turkey Creek (TCB)
Lab # 5079

Depth	NaCl (lb/yd^3)			
(mm)	A	B	C	AVG
1.00	28.194	27.837	27.908	27.980
3.00	21.143	21.023	21.023	21.063
5.00	14.089	14.089	13.962	14.047
7.00	10.707	10.489	10.430	10.542
9.00	8.336	8.122	7.789	8.082
11.00	5.869	5.748	5.986	5.868
15.18	2.699	2.681	2.714	2.698
21.53	0.748	0.773	0.736	0.752
27.88	0.399	0.407	0.404	0.403
34.23	0.359	0.388	0.411	0.386

Bridge Turkey Creek (TCB)
Lab # 5080

Depth	NaCl (lb/yd^3)			
(mm)	A	B	C	AVG
1.00	30.194	30.474	30.039	30.236
3.00	24.939	34.464	25.219	28.207
5.00	16.425	16.257	16.663	16.448
7.00	13.378	13.398	13.060	13.279
9.00	9.990	10.331	10.372	10.231
11.00	6.699	6.790	6.746	6.745
15.18	2.893	2.930	2.902	2.908
21.53	0.665	0.673	0.679	0.672
27.88	0.305	0.346	0.329	0.327
34.23	0.276	0.260	0.263	0.266

Bridge New Roosevelt (NRB)
Lab # 5075

Depth	NaCl (lb/yd^3)			
(mm)	A	B	C	AVG
1.00	15.410	14.872	14.674	14.985
3.00	21.570	22.262	21.926	21.919
5.00	19.279	19.279	19.575	19.378
7.00	16.989	17.213	17.144	17.115
9.00	15.694	15.593	15.784	15.690
11.00	13.353	13.481	13.530	13.455
15.18	8.330	8.465	8.497	8.431
21.53	2.973	2.856	3.172	3.000
27.88	0.467	0.420	0.490	0.459
34.23	0.315	0.327	0.343	0.328

Field Tests 4. Chloride Profile Testing Results of Cored Samples (Cont.).

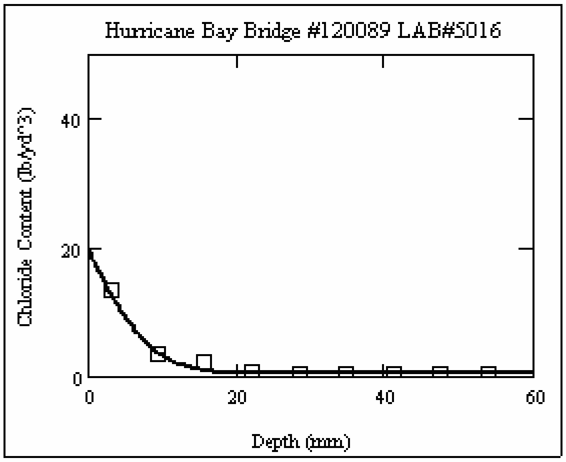
Bridge New Roosevelt (NRB)
Lab # 5076

Depth	NaCl (lb/yd^3)			
(mm)	A	B	C	AVG
1.00	14.954	14.833	15.161	14.983
3.00	14.049	14.165	14.162	14.125
5.00	13.676	13.814	13.712	13.734
7.00	14.504	14.612	14.603	14.573
9.00	16.213	16.186	16.358	16.252
11.00	15.562	15.595	15.438	15.532
15.18	13.960	13.934	14.240	14.045
21.53	5.197	5.876	5.986	5.686
27.88	3.265	3.288	3.252	3.268
34.23	0.401	0.416	0.417	0.411

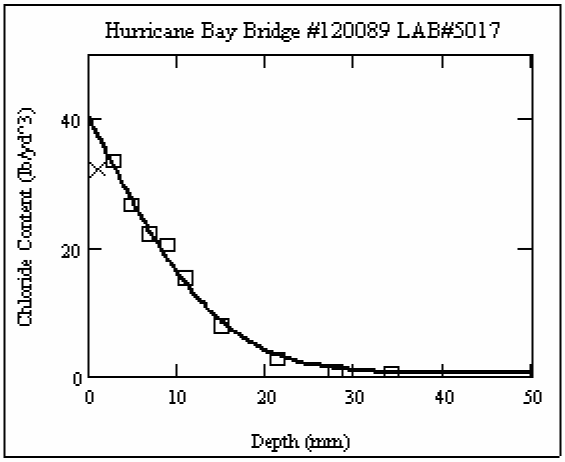
Bridge New Roosevelt (NRB)
Lab # 5077

Depth	NaCl (lb/yd^3)			
(mm)	A	B	C	AVG
1.00	17.903	17.903	17.816	17.874
3.00	23.959	23.888	24.035	23.961
5.00	21.334	21.872	21.374	21.527
7.00	19.257	19.140	19.134	19.177
9.00	16.463	16.652	16.576	16.564
11.00	14.474	14.926	14.789	14.730
15.18	10.243	10.398	9.955	10.199
21.53	2.528	2.576	2.588	2.564
27.88	0.513	0.526	0.507	0.515
34.23	0.246	0.270	0.256	0.257

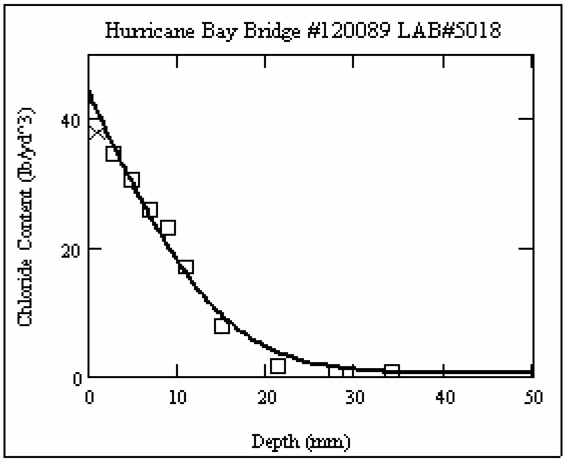
Field Tests 5. Diffusion Coefficient Results of Cored Samples.



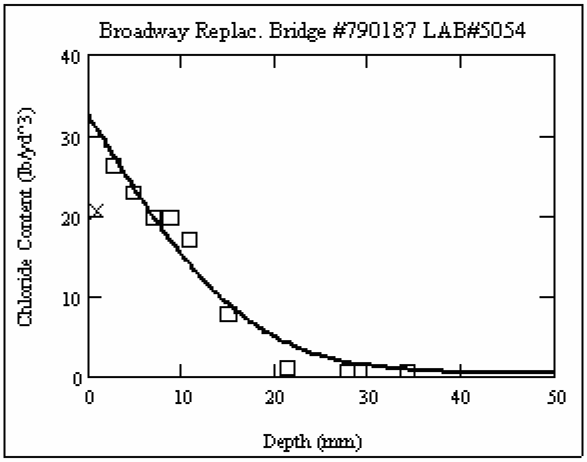
Diffusion(m^2/sec)	4.994E-14	**Background(lb/yd^3)**	0.547
Surface(lb/yd^3)	20.336	**R^2 Value**	0.9937



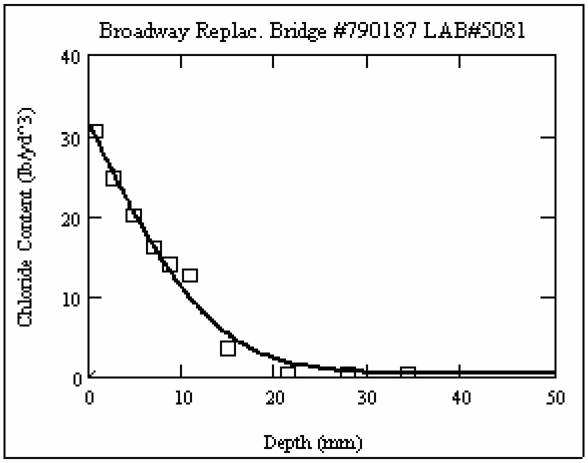
Diffusion(m^2/sec)	1.487E-13	**Background(lb/yd^3)**	0.533
Surface(lb/yd^3)	41.112	**R^2 Value**	0.9975



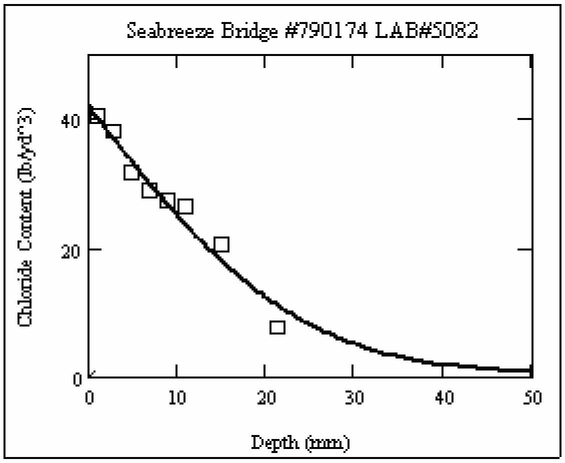
Diffusion(m^2/sec)	1.511E-13	**Background(lb/yd^3)**	0.561
Surface(lb/yd^3)	44.904	**R^2 Value**	0.9949



Diffusion(m^2/sec)	5.854E-13	**Background(lb/yd^3)**	0.467
Surface(lb/yd^3)	33.012	**R^2 Value**	0.9830

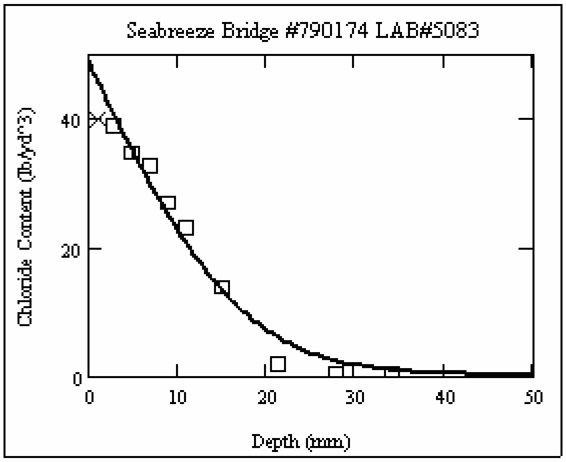


Diffusion(m^2/sec)	3.578E-13	**Background(lb/yd^3)**	0.467
Surface(lb/yd^3)	32.401	**R^2 Value**	0.9937

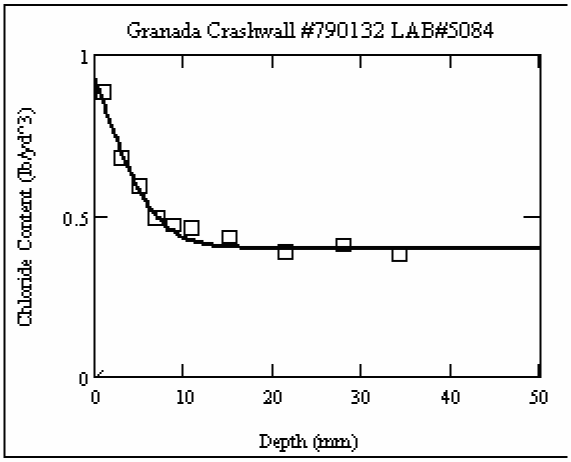


Diffusion(m^2/sec)	6.280E-13	**Background(lb/yd^3)**	0.467
Surface(lb/yd^3)	42.497	**R^2 Value**	0.9803

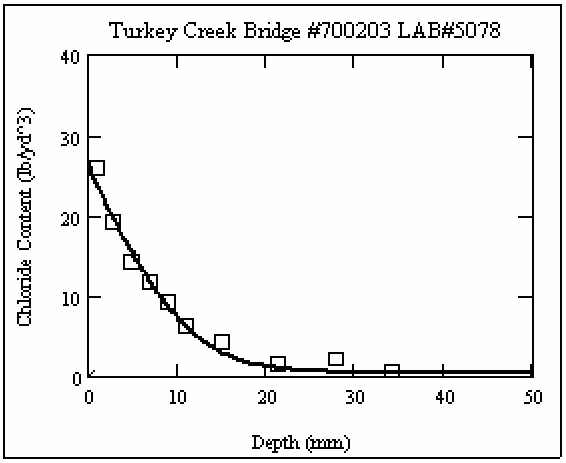
Field Tests 6. Diffusion Coefficient Results of Cored Samples (Cont.).



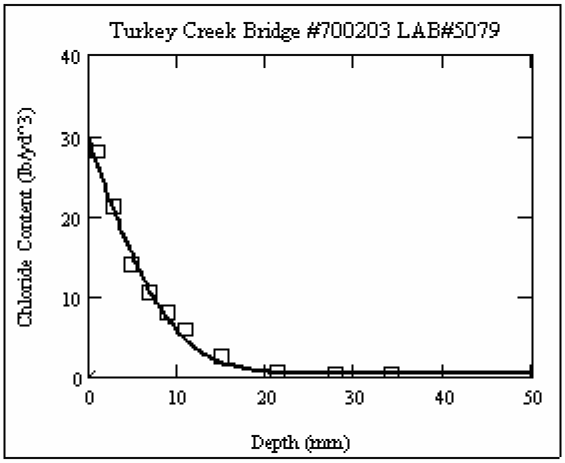
Diffusion(m^2/sec)	3.291E-13	**Background(lb/yd^3)**	0.432
Surface(lb/yd^3)	49.660	**R^2 Value**	0.9910



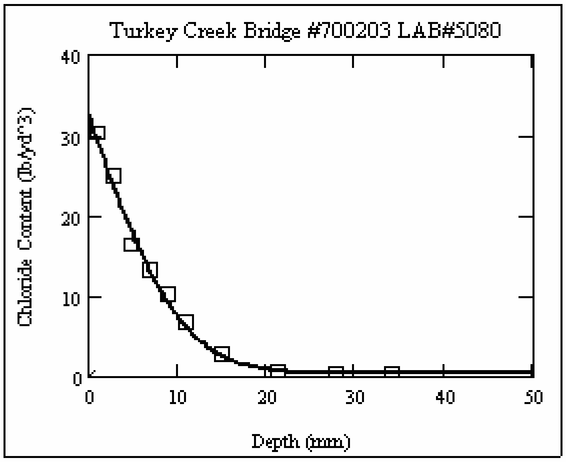
Diffusion(m^2/sec)	5.077E-14	**Background(lb/yd^3)**	0.400
Surface(lb/yd^3)	0.942	**R^2 Value**	0.9893



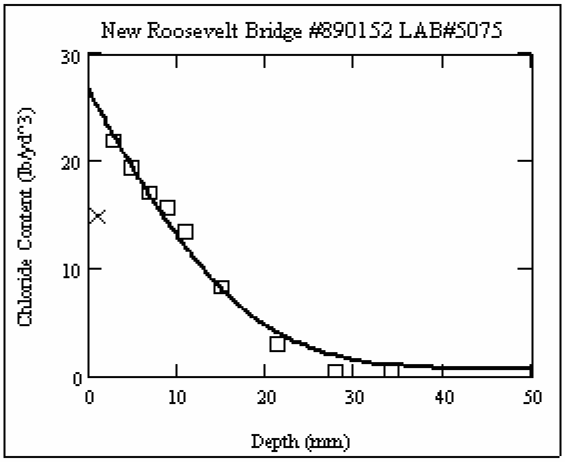
Diffusion(m^2/sec)	1.854E-13	**Background(lb/yd^3)**	0.556
Surface(lb/yd^3)	26.791	**R^2 Value**	0.9936



Diffusion(m^2/sec)	1.316E-13	**Background(lb/yd^3)**	0.423
Surface(lb/yd^3)	30.269	**R^2 Value**	0.9965

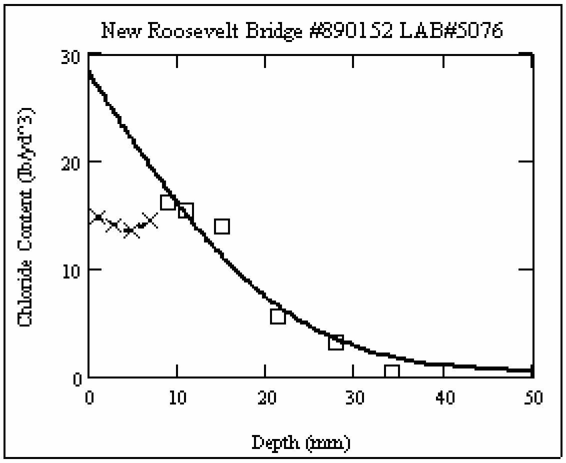


Diffusion(m^2/sec)	1.553E-13	**Background(lb/yd^3)**	0.417
Surface(lb/yd^3)	33.237	**R^2 Value**	0.9974

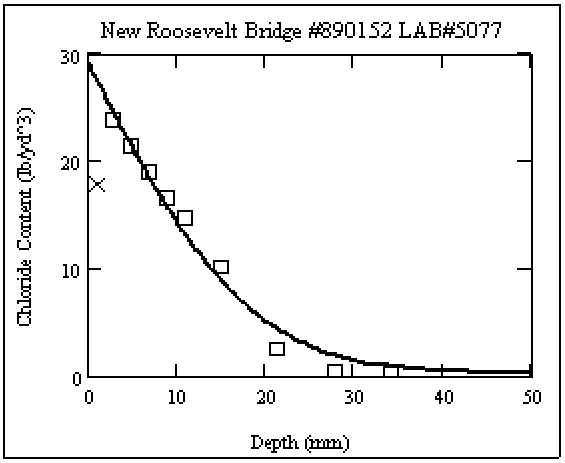


Diffusion(m^2/sec)	3.606E-13	**Background(lb/yd^3)**	0.614
Surface(lb/yd^3)	27.046	**R^2 Value**	0.9946

Field Tests 7. Diffusion Coefficient Results of Cored Samples (Cont.).



Diffusion(m^2/sec)	5.404E-13	**Background(lb/yd^3)**	0.432
Surface(lb/yd^3)	28.700	**R^2 Value**	0.9757



Diffusion(m^2/sec)	3.727E-13	**Background(lb/yd^3)**	0.382
Surface(lb/yd^3)	29.696	**R^2 Value**	0.9936

APPENDIX E

ANALYSIS OF DATA OBTAINED FROM OTHER PROJECTS.

Appendix Table of Contents

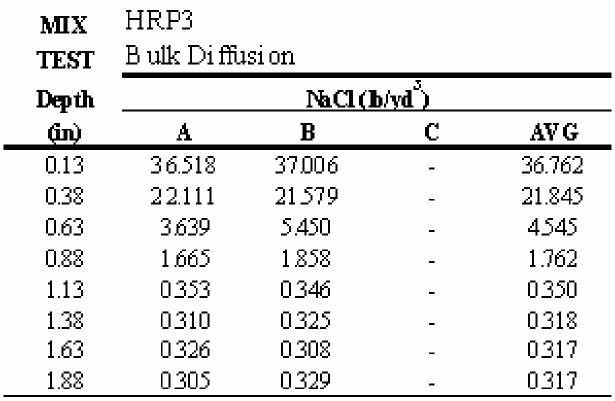
External_Projects 1. HRP Project (Paredes 2007) Concrete Mixture Designs.

Mixture	Materials and Specifications					
	FDOT Class	W/C	Cementicious (pcy)	Pozzolan (%Cement.)	Pozzolan (%Cement.)	Coarse Aggregate
HRP3	V	0.35	752	Fly-Ash (20%)	Silica Fume Slurry (8%)	89 Limestone
HRP4	V	0.35	752	Fly-Ash (20%)	Silica Fume Densified (8%)	89 Limestone

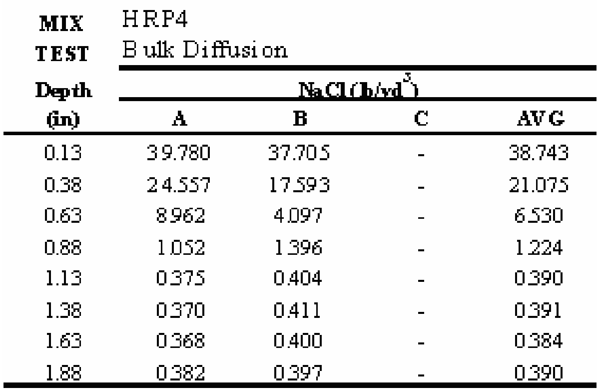
External_Projects 2. Initial Chloride Background Levels from HRP Project (Paredes 2007).

TEST	Initial Chloride Background Levels			
MIX	NaCl (lb/yd^3)			
	A	B	C	AVG
HRP3	0.426	0.426	0.435	0.429
HRP4	0.310	0.368	0.344	0.341

External_Projects 3. 364-Day Bulk Diffusion Chloride Profile Testing from HRP Project (Paredes 2007).

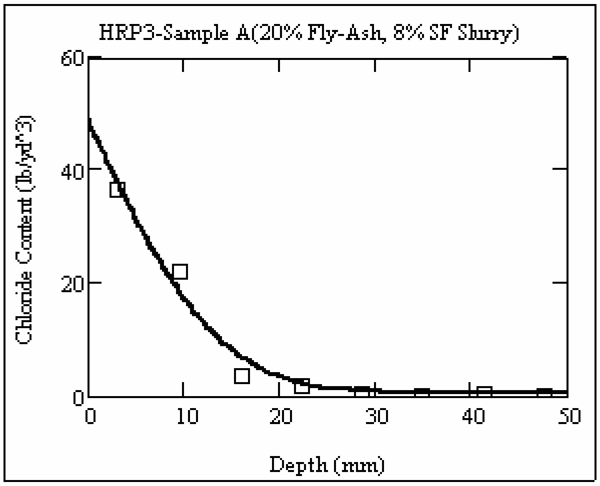


MIX	HRP3			
TEST	Bulk Diffusion			
Depth (in)	NaCl (lb/yd^3)			
	A	B	C	AVG
0.13	36.518	37.006	-	36.762
0.38	22.111	21.579	-	21.845
0.63	3.639	5.450	-	4.545
0.88	1.665	1.858	-	1.762
1.13	0.353	0.346	-	0.350
1.38	0.310	0.325	-	0.318
1.63	0.326	0.308	-	0.317
1.88	0.305	0.329	-	0.317

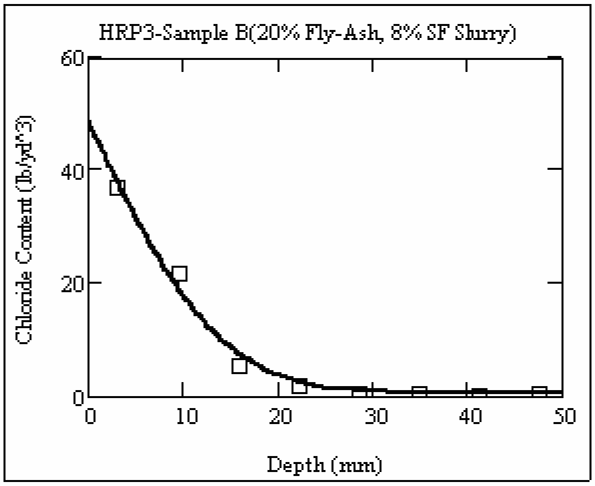


MIX	HRP4			
TEST	Bulk Diffusion			
Depth (in)	NaCl (lb/yd^3)			
	A	B	C	AVG
0.13	39.780	37.705	-	38.743
0.38	24.557	17.593	-	21.075
0.63	8.962	4.097	-	6.530
0.88	1.052	1.396	-	1.224
1.13	0.375	0.404	-	0.390
1.38	0.370	0.411	-	0.391
1.63	0.368	0.400	-	0.384
1.88	0.382	0.397	-	0.390

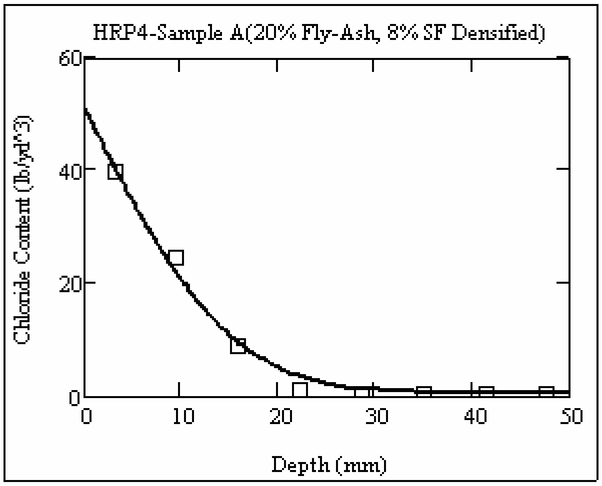
External_Projects 4. Diffusion Coefficient Results from HRP Project (Paredes 2007).



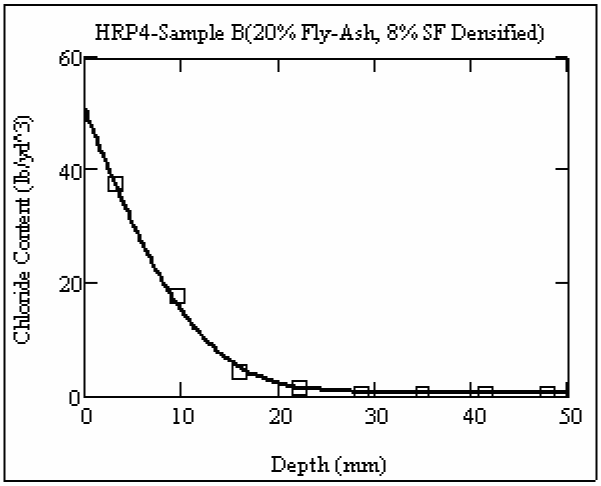
Diffusion(m^2/sec)	1.691E-12	**Background(lb/yd^3)**	0.429
Surface(lb/yd^3)	49.517	**R^2 Value**	0.9901



Diffusion(m^2/sec)	1.782E-12	**Background(lb/yd^3)**	0.429
Surface(lb/yd^3)	49.372	**R^2 Value**	0.9955



Diffusion(m^2/sec)	2.071E-12	**Background(lb/yd^3)**	0.429
Surface(lb/yd^3)	52.171	**R^2 Value**	0.9955



Diffusion(m^2/sec)	1.355E-12	**Background(lb/yd^3)**	0.429
Surface(lb/yd^3)	51.815	**R^2 Value**	0.9990

External_Projects 5. St. George Island Bridge Pile Testing Project Chloride Profile Testing of Cored Samples (Cannon et al. 2006).

Pile 44-2
Loaction SUBMERGED ZONE (6-ft below MHW)

Depth	**NaCl (lb/yd^3)**			
(in)	**A**	**B**	**C**	**AVG**
0.25	30.239	30.746	30.042	30.342
0.75	24.310	24.339	24.339	24.329
1.50	20.436	20.041	20.261	20.246
2.50	19.451	19.161	19.585	19.399
3.50	14.732	14.610	14.703	14.682
4.50	13.604	13.630	13.777	13.670
5.50	14.549	14.298	14.404	14.417

Pile 44-2
Loaction TIDAL ZONE (1-ft below MHW)

Depth	**NaCl (lb/yd^3)**			
(in)	**A**	**B**	**C**	**AVG**
0.25	18.569	18.985	18.884	18.813
0.75	16.492	16.927	17.017	16.812
1.50	17.062	16.861	17.247	17.057
2.50	14.018	14.111	14.355	14.161
3.50	12.435	12.630	12.794	12.620
4.50	11.067	10.961	10.957	10.995
5.50	10.260	10.596	9.963	10.273

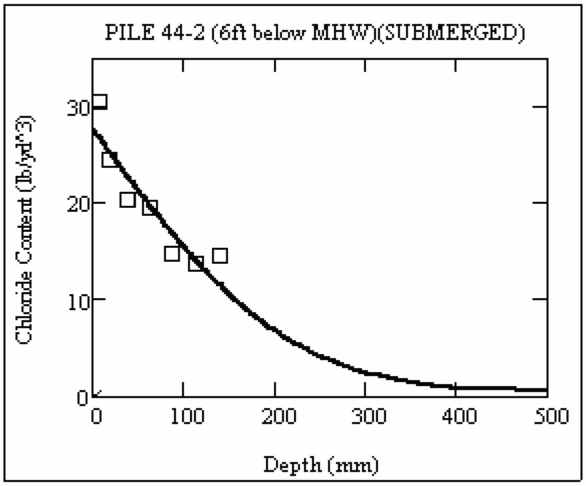
Pile 44-2
Loaction SPLASH ZONE (3-ft above MHW)

Depth	**NaCl (lb/yd^3)**			
(in)	**A**	**B**	**C**	**AVG**
0.25	20.062	19.933	19.801	19.932
0.75	16.966	16.973	17.258	17.066
1.50	13.277	13.447	13.320	13.348
2.50	8.979	8.879	9.026	8.961
3.50	5.999	5.866	5.866	5.910
4.50	3.739	3.550	3.374	3.554
5.50	1.652	1.648	1.655	1.652

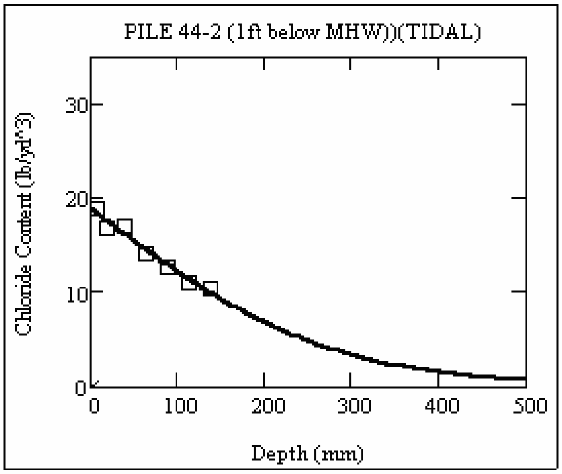
Pile 44-2
Loaction DRY ZONE (7-ft above MHW)

Depth	**NaCl (lb/yd^3)**			
(in)	**A**	**B**	**C**	**AVG**
0.25	5.122	5.115	5.198	5.145
0.75	7.310	7.203	6.771	7.095
1.50	5.223	5.175	5.191	5.196
2.50	3.536	3.462	3.454	3.484
3.50	1.672	1.745	1.666	1.694
4.50	1.013	0.958	1.021	0.997
5.50	0.371	0.384	0.355	0.370

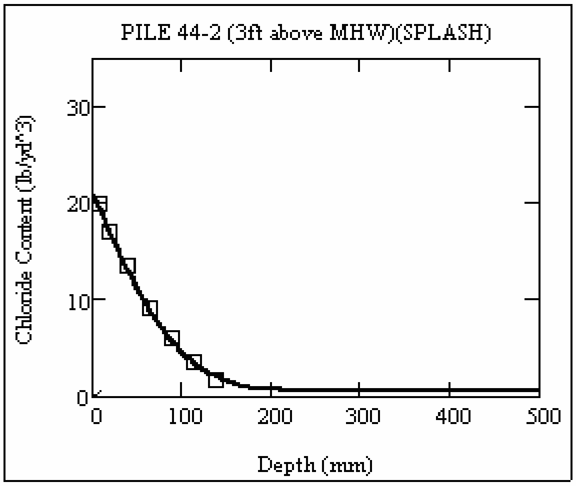
External_Projects 6. St. George Island Bridge Pile Testing Project Diffusion Coefficients(*) (Cannon et al. 2006).



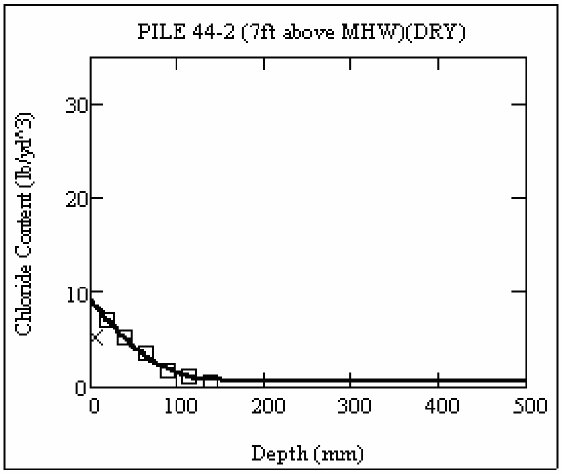
Diffus ion(m^2/sec)	1.148E-11	**Background(lb/yd^3)**	0.400
Surface(lb/yd^3)	27.738	**R^2 Value**	0.9258



Diffus ion(m^2/sec)	1.827E-11	**Background(lb/yd^3)**	0.400
Surface(lb/yd^3)	18.879	**R^2 Value**	0.9855



Diffus ion(m^2/sec)	2.495E-12	**Background(lb/yd^3)**	0.400
Surface(lb/yd^3)	21.163	**R^2 Value**	0.9997



Diffus ion(m^2/sec)	1.646E-12	**Background(lb/yd^3)**	0.400
Surface(lb/yd^3)	9.219	**R^2 Value**	0.9978

(*) Initial chloride background levels information was not available in this project. Therefore, it was assumed a minimum value of 0.40 lb/yd^3 for all the samples.