WISCONSIN HIGHWAY RESEARCH PROGRAM # 0092-03-09

EVALUATION OF CONCRETE DECK AND CRACK SEALERS

By

José A. Pincheira
Melissa A. Dorshorst

Department of Civil and Environmental Engineering
University of Wisconsin-Madison

Submitted to the Wisconsin Department of Transportation
December 2005

Disclaimer

This research was funded through the Wisconsin Highway Research Program by the Wisconsin Department of Transportation and the Federal Highway Administration under Project # (0092-03-09). The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Wisconsin Department of Transportation or the Federal Highway Administration at the time of publication.

Technical Report Documentation Page

1. Report No. WHRP 06-09	2. Government Accession No	3. Recipient's Catalog No

4. Title and Subtitle EVALUATION OF CONCRETE DECK AND CRACK SEALERS	5. Report Date December 3, 2005 6. Performing Organization Code
7. Authors José A. Pincheira, Ph.D., and Melissa A. Dorhorst	8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil and Environmental Engineering University of Wisconsin-Madison 1415 Engineering Drive Madison, WI 53706	10. Work Unit No. (TRAIS) 11. Contract or Grant No. SPR 0092-03-09
12. Sponsoring Agency Name and Address Wisconsin Department of Transportation 4802 Sheboygan Avenue Madison WI 73707-7965	13. Type of Report and Period Covered Final Report March 2003 – December 2005 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The primary objective of this study was to assess the effectiveness and relative performance of commercially available concrete bridge deck and crack sealants. A total of thirteen deck sealants and ten crack sealants were selected for study under laboratory conditions that simulated the exposure to deicing salts and freeze-thaw cycles encountered in practice. Based on the results of this study, sealants that offered the best performance were assigned to Performance Group Category I, those that offered a moderate level of protection were assigned to Performance Group Category II, and those that offered the least amount of protection were assigned to Performance Group Category III. Of the thirteen deck sealants studied, two products (Sonneborn Penetrating Sealer 40 VOC and Hydrozo Silane 40 VOC) surpassed the rest and thus they were assigned to Performance Category I. Six other sealants offered moderate protection and were assigned to Performance Category II. The remaining five sealants offered the least protection and were assigned to Performance Category III. The performance of crack sealants depended on the crack width considered. Of the ten sealants tested in this study, Sikadur 55 SLV showed excellent performance in hairline, narrow and medium cracks and was assigned to Performance Group Category I. Dural 335 also performed very well in the crack size recommended by the manufacturer, i.e., hairline cracks and was also assigned to Performance Group Category I. Three other sealants performed well in hairline, narrow, and medium cracks when not exposed to freeze-thaw cycles, but were adversely affected by freeze-thaw cycles and were assigned to Performance Group Category II. The remaining crack sealants showed low bond strengths, large reductions in strength when exposed to freeze-thaw cycles and were assigned to Performance Group Category III. Only two products were tested in specimens with wide crack widths. Their performance was poor and thus they were assigned to Performance Group Category III.

17. Key Words Deck sealants, crack sealants, durability, freeze-thaw cycles, concrete bridge decks	18. Distribution Statement No restriction. This document is available to the public through the National Technical Information Service 5285 Port Royal Road Springfield VA 22161

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

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

Executive Summary

Deicing salts, mixtures of sodium chloride and calcium chloride, are commonly broadcast over bridge decks during Wisconsin winters. As ice melts and mixes with the deicing salt, chloride ions can penetrate into the concrete and induce corrosion of the reinforcing bars, or penetrate through cracks and cause deterioration of the steel or concrete substructure. The use of deck and crack sealants is one method to prevent chloride ion intrusion and the subsequent deterioration of the deck or the substructure. Although sealants are commonly used, little is known about their performance. Additionally, the effectiveness of sealants exposed to freezing and thawing cycles such as those encountered in Wisconsin is unknown.

The primary objective of this study was to assess the effectiveness and relative performance of commercially available concrete bridge deck and crack sealants. To meet this objective, a total of thirteen deck sealants and ten crack sealants were selected for study under laboratory conditions that simulated the exposure to deicing salts and freeze-thaw cycles encountered in practice.

The study on deck sealants was divided into two components. In the first component, sealant performance was assessed by measuring the resistance to chloride ion intrusion in concrete specimens ponded with a sodium chloride solution, in accordance with the provisions of AASHTO T 259. Specimens with and without exposure to freeze-thaw cycles were included in the study. After ponding of the specimens was completed, samples were removed and tested for chloride ion content in accordance with AASHTO T 260.

In the second component, separate specimens were cast to measure the depth of penetration profile of the sealants using a dye method. These data were used to identify a relationship between penetration depth and resistance to chloride ion intrusion of the deck sealants.

The study on crack sealants was also divided into two components. In the first component, sealant performance was assessed by measuring its ability to penetrate and fill cracks of prescribed widths. Four crack widths, representative of those encountered in practice, were considered in this study: hairline, narrow, medium and wide cracks. In the second component of the study, the bond strength and durability of the sealants was assessed. The bond strength of the crack sealants was measured in specimens with and without

exposure to freeze-thaw cycles in order to evaluate the possible deterioration of the sealants under extreme environmental conditions.

Based on the results of this study, deck and crack sealants were assigned to a performance group category depending on their measured performance. Sealants that offered the best performance were assigned to Performance Group Category I, those that offered a moderate level of protection were assigned to Performance Group Category II, and those that offered the least amount of protection were assigned to Performance Group Category III.

Of the thirteen deck sealants studied, two products (Sonneborn Penetrating Sealer 40 VOC and Hydrozo Silane 40 VOC) surpassed the rest and thus they were assigned to Performance Category I. They exhibited the best performance, had the largest depths of penetration and met the current WisDOT acceptance criteria. Six other sealants offered moderate protection and were assigned to Performance Category II. These sealants had shallower penetration depths, their performance severely declined when exposed to freeze-thaw cycles, and they did not meet the current WisDOT acceptance criteria. The remaining five sealants offered the least protection and were assigned to Performance Category III.

The performance of crack sealants depended in part on the crack width considered. Of the ten sealants tested in this study, Sikadur 55 SLV showed excellent performance in hairline, narrow and medium cracks and was assigned to Performance Group Category I. Dural 335 also performed very well in the crack size recommended by the manufacturer, i.e., hairline cracks and was also assigned to Performance Group Category I. Three other sealants performed well in hairline, narrow, and medium cracks when not exposed to freeze-thaw cycles. However, their performance was more adversely affected by freeze-thaw cycles and thus they were assigned to Performance Group Category II. The remaining crack sealants did not perform as well and showed low bond strengths, and large reductions in strength when exposed to freeze-thaw cycles and were assigned to Performance Group Category III. Only two products were tested in specimens with wide crack widths. Their performance was poor and thus they were assigned to Performance Group Category III.

Acknowledgements

The financial support provided by the Wisconsin Highway Research Program is gratefully acknowledged. The authors would like to thank Messrs. Bruce Karow, WisDOT, James Parry, WisDOT Materials Laboratory, Thomas Strock, FHWA, and John Bolka, District 2, WisDOT, members of the Project Oversight Committee assigned to this study for their input throughout this project. Thanks are also extended to District Bridge Maintenance Engineers for their input concerning the practical aspects of this project by responding the survey on the use of deck and crack sealants. Special thanks are due to Jim Parry, David Hutchinson and Ryan Murray of the WisDOT Materials Laboratory for their technical support in the early stages of this study. The following companies: Wingra Stone, Yahara Materials and LaFarge Corporation provided the aggregates and cement used in this project. Their support is gratefully acknowledged. The support of Professor Steven Cramer, Director, Bill Lang and Carole Kraak of the Wisconsin Structures and Materials Testing Laboratory (WSMTL) is greatly appreciated. The assistance of undergraduate students at various stages of this investigation is gratefully acknowledged.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Introduction

Deicing salts, which are generally mixtures of sodium chloride and calcium chloride, are commonly broadcast over bridge decks during Wisconsin winters. As ice melts, it mixes with the deicing salt to form a salt water solution, which remains ponded on the surface of the bridge deck. Although the use of epoxy coated bars has served to deter corrosion of reinforcing bars in bridge decks built in the last 20 to 25 years, chlorides may penetrate into the deck and/or through cracks, and induce corrosion of the steel substructure, or of the reinforcing steel bars in the case of a concrete substructure.

To prevent chloride ion intrusion, decks can be protected by spraying water repellents on the surface of the deck. The Wisconsin Department of Transportation (WisDOT) maintains a list of penetrating water repellent deck sealers that have been approved for use on concrete bridge decks. Deck sealers currently available are primarily silanes and siloxanes (derivatives of silicone), and are intended to be applied during the final stages of construction to protect the deck against chloride ion intrusion. While some WisDOT Districts have used these products to reseal bridge decks on a regular cycle, little is known about the performance of the sealants over the long term. Bridge decks can be subjected to vehicle abrasion, which may “wear off” a penetrating sealant and reduce its effectiveness over time. In addition, the effectiveness of deck sealants exposed to freezing and thawing cycles normally encountered in Wisconsin is unknown. Sealant performance is not the only criteria, however, to consider when selecting a product. Depending on the specific needs of the project, other sealant characteristics, such as material cost and time to open to traffic may be as important to consider as the performance of the sealant when choosing a product.

In addition to protecting newly constructed bridge decks, cracks in existing decks should be sealed to prevent chloride ion intrusion. Many concrete bridge decks in the United States have developed transverse cracks shortly after construction (Krauss and Rogalla, 1996). The cracks sometimes extend through the full depth of the deck and are usually spaced three to 10 feet apart along the length of the bridge. Consequently, chlorides can penetrate into the deck through the cracks, even if the deck was properly sealed at the time of construction. Crack sealants are often used to penetrate, fill, and bond existing cracks to prevent chloride ion intrusion. These sealants are expected to bridge and seal fine cracks in a deck by creating a barrier that prevents water and water-borne contaminants from entering the concrete. Also, they must be able to endure crack opening and closing due to thermal effects and deck movements. Currently available crack sealant products include High Molecular Weight Methacrylates (HMWM) resins, epoxy resins, and urethane resins among others.

Similar to deck sealants, the performance of crack sealants is often unknown and difficult to quantify. Currently, there are no standard test methods to measure the bond strength of a sealer at a crack. Also, the effectiveness of crack sealants may be affected by several parameters such as, the procedure used to apply the crack sealer, the crack width and depth, and the existing condition of the crack. Various procedures can be used to improve the penetration of crack sealants, e.g., pressure washing or sandblasting. However, measuring sealant penetration provides only qualitative insight as to the ability of the sealant to bond to concrete, and it will not provide a quantitative measure of the bond strength.

1.2 Objectives

The primary objective of this study was to assess the effectiveness and performance of concrete bridge deck and crack sealants. To accomplish the project goal, the study was divided into two main tasks. In the first task, the ability of selected deck sealants to improve the resistance of concrete to the ingress of chloride ions was evaluated by ponding and chloride ion analysis tests. Also, the depth of penetration of the sealants was measured to establish a correlation between sealant penetration and the ability to deter chloride ion intrusion. In the second task, the effectiveness of the selected crack sealants to both penetrate cracks and to bond to crack walls was evaluated for various crack widths. For this purpose, test procedures were developed to measure the penetration depth of the sealants, and to test the sealant bond strength.

1.3 Scope

The project considered thirteen deck sealants and ten crack sealants that were selected for laboratory testing in consultation with the Project Oversight Committee (POC). Commercially available solvent and water-based deck sealants were both included in this study. The crack sealants selected for testing included High Molecular Weight Methacrylates (HMWM) resins, epoxy resins, and urethane resins. Following the recommendations of the POC, a Grade D concrete mix design as designated in the Wisconsin Bridge Manual was used for all concrete specimens.

The deck sealant component of the study included ponding and chloride ion analysis tests performed in accordance with the provisions of AASHTO T 259/260. The effect of freeze-thaw cycles on the performance of the deck sealants was also evaluated. Bond strength of crack sealants was evaluated for four crack widths as defined in the current WisDOT Bridge Inspection Pocket Manual. Freeze-thaw cycle tests using ASTM C 666 were also used in the crack sealant component of the study to evaluate the durability of the sealants.

Chapter 2

Background and Literature Review

2.1 Introduction

In this chapter, the main characteristics of deck and crack sealants are presented and discussed. Also, the most commonly used methods for evaluating concrete treated with sealers are described, including the standard test methods used in this test program, and a summary of previous experimental studies of deck and crack sealants is presented.

2.2 Characteristics of Deck and Crack Sealants

There are many criteria to consider when selecting a deck or crack sealant for use on a bridge deck. Characteristics such as depth of penetration and weather resistance provide information on the expected performance of a product, while others offer information related to field preparation and application procedures. A myriad of products were reviewed and categorized according to the criteria described in the following sections. This information was later used to conduct a preliminary evaluation of the effectiveness and performance of the sealants, and ultimately select the products used in the test program described in subsequent sections of this report.

2.2.1 Chemical family

Deck sealants – Most of the concrete deck sealers in use are based on silicone technology, primarily silanes and siloxanes. These materials are derivatives of silicone with molecules small enough to penetrate and bond to the concrete, creating a hydrophobic layer in the treated region. Since they are sealers and not membranes, they do not provide an impenetrable physical barrier, but rather reduce water inflow by inducing a chemical repulsion of the concrete to water (Aitken and Litvan, 1989). Silanes and siloxanes are usually supplied as a solution or as a suspension in a solvent.

Crack sealants – Currently available crack sealant products include High Molecular Weight Methacrylates (HMWM) resins, epoxy resins, and urethane resins among others.

Crack sealant products are able to bridge and seal fine cracks in a deck by creating a barrier that prevents water and water-borne contaminants from entering the concrete.

2.2.2 Volatile Organic Compound (VOC) content

Volatile Organic Compounds (VOCs) are emitted as gases from certain solids or liquids. VOCs include a variety of chemicals, some of which are commonly found in concrete sealers and treatments, and may have short- and long-term adverse health effects. In addition, ground level ozone, a major component of "smog," is formed in the atmosphere when VOCs and oxides of nitrogen react in the presence of sunlight. A study conducted by the United States Environmental Protection Agency (EPA) found that architectural coatings were one of the largest VOC emission sources among consumer and commercial product categories (EPA, 2005). In an effort to reduce the harmful health effects associated with VOC exposure and the production of ozone, the EPA imposed VOC content limits for architectural coatings, including waterproofing sealers and treatments. Waterproofing sealers and treatments were limited to 5.0 pounds per gallon, or 600 grams per liter, with an exceedance fee charged to manufacturers whose products exceeded the limit. The VOC content, listed on technical data sheets (TDS) and material safety data sheets (MSDS), can be used as a general indicator of the health risks associated with a product. The VOC content of similar performing products should be considered when selecting a product for use to avoid unnecessary overexposure to VOCs.

2.2.3 Recommended surface preparation requirements

The amount and type of surface preparation required before a product is applied to a surface or crack is important to consider when selecting a sealant. The amount of time, effort, and equipment required to prepare a surface could significantly increase the overall cost of a product. This additional cost could make a product with a higher material but lower preparation costs a more economical option. Recommended surface preparation requirements are provided by the manufacturer for each product. Typical surface preparation requirements for deck and crack sealants range from no specific requirements, to pressure washing or mechanical abrasion to clean the deck surface or remove debris from cracks. In addition, the necessary moisture content of the substrate at the time of application can be included in the surface preparation category and can range from completely dry to slightly damp.

2.2.4 Environmental conditions

The environmental state of a deck during and shortly after application of a sealant may be an important criterion to consider when selecting a product. The acceptable temperature range of the substrate during and immediately after application of deck or crack sealants is included in this category, as well as expected precipitation conditions after application. For some products, for example, the acceptable temperature range during application of a product may be between 40°F and 100°F, but the product should not be applied if the temperature is expected to drop below 40°F or if rain or inclement weather is expected within 12 hours. Others, however, may be applied to 20°F and the substrate need be protected from rain for only four hours after application. In general, products that can be applied within a broader range of environmental conditions will be more attractive since they will give Departments of Transportation and contractors more flexibility in deciding when to seal cracks or an entire deck.

2.2.5 Application methods

Deck sealants – Recommended methods for applying deck sealants typically consist of spraying the product on the deck with a low-pressure sprayer, or using a roller or squeegee to spread the sealant over the deck. Both methods are usually relatively quick and inexpensive to perform.

Crack sealants – The application method is a key aspect to consider when evaluating crack sealants because it directly affects the time and equipment required to seal cracks. While gravity-fed sealants are commonly available on the market, some products are designated as pressure injection only. Pressure injecting cracks requires special equipment and will often be more time consuming than gravity feeding cracks. While pressure injection may be a viable option for some Wisconsin Department of Transportation (WisDOT) districts, the equipment used to pressure inject cracks is not readily available to all. In addition, the cost to rent or purchase the necessary equipment, or hire a contractor to pressure injects cracks, combined with the extra time the deck would need to be closed to traffic could make a product with relatively inexpensive material costs become extremely expensive.

2.2.6 Coverage rate and cost

The coverage rate and cost of sealant products can vary significantly and can have a considerable impact on whether or not to choose a particular product. For deck sealants, coverage rates are typically given in square feet of coverage per gallon, which combined with cost of the product gives an equivalent cost per square foot of coverage.

For crack sealants, however, the coverage rate will vary depending on how the product is applied. When used to seal individual cracks only, the volume of sealant needed to fill a crack is the volume of the crack. However, to seal many fine or hairline cracks in a deck, some products can be broadcast over the entire deck in a manner similar to deck sealant application methods. For products with this last application option, the coverage rate can be calculated in square feet per gallon.

2.2.7 Time to open to traffic

The amount of time that entire bridge decks or individual lanes of traffic have to be closed for bridge maintenance and repair is a key factor to consider when choosing a sealant product. The time required to actually apply most deck sealants is generally very similar, and will probably vary more depending on the type and size of the equipment used rather than on the sealant product itself. The time required to apply crack sealants is generally a function of the size and number of cracks, as well as the application method, i.e., gravity-fed or pressure injection. However, the drying and curing time after application before a deck can be reopened to traffic can vary substantially among products. Some quick setting crack sealants become tack free in 15 minutes and are fully cured within 45 minutes. In contrast, some of the slower-drying deck and crack sealants may require up to 12 hours of drying time before the deck can be reopen to traffic.

2.2.8 Expected durability

The expected durability of a product is the manufacturers' estimate of the number of years a product will continue to remain effective before reapplication is necessary. In most cases, product manufacturers can only provide very rough estimates of the expected durability, as every bridge deck experiences different weather and traffic conditions, and the sealant on each bridge deck will wear away at a different rate. Recognizing the uncertainty in the manufacturers' estimates, the expected durability must be interpreted with caution. The expected durability for deck sealants typically ranges from five years to 15 years, while crack sealants are usually expected to remain effective from five years up to the life of the structure for some products.

2.2.9 Freeze-thaw resistance

Freeze-thaw resistance is crucial to effective performance of sealant products applied to bridge decks in Wisconsin. Since there is not a standard test performed on all the sealants by the manufacturers to measure freeze-thaw resistance, the likelihood of a sealant performing well under freeze-thaw conditions must be established based on product manufacturers' recommendations. Clearly, sealants which are not recommended for use in freeze-thaw conditions should not be considered for use on Wisconsin bridge decks.

2.2.10 Depth of penetration - Deck sealants

The depth of penetration of a sealant is the approximate thickness of the hydrophobic layer of concrete that prevents chloride ion ingress, and it may be correlated with the sealant's ability to remain effective over time. A sealant with a large depth of penetration, however, will not necessarily be effective at slowing the ingress of water and other contaminants, but it will likely perform better over time than a sealant with a very shallow penetration depth. Sealants with shallow penetration depths are removed more quickly from the surface of a bridge deck due to vehicle abrasion, while sealants with larger depths of penetration provide a remaining layer of sealant even after abrasion. Manufacturer reported depths of penetration of deck sealants typically ranges from as shallow as 1/8 inch to as deep as ¾ inch.

2.2.11 Applicable crack width - Crack sealants

Crack sealants are generally designed to be used for a range of crack widths. However, some sealants, generally those with very low viscosity, are recommended to be used only for fine, hairline cracks, while others can be used only for wider cracks. The applicable crack width range for sealants should be considered when selecting products to seal cracks of varying sizes.

2.3 Methods for Evaluating Concrete Treated with Sealers

Various test procedures are available to assess the performance of concrete treated with sealers. Some test methods include provisions specifically designed to evaluate sealed concrete, while other test methods designed to test plain concrete can be adapted to test the effectiveness of concrete treated with sealers. Tests that measure chloride ion intrusion and sealant depth of penetration are well suited for evaluating the performance of deck sealants. Modified versions of the splitting tensile strength of concrete cylinders and freeze-thaw resistance tests provide methods for evaluating the bond strength and durability of crack sealants. These methods are briefly described in the following sections.

2.3.1 Chloride Ion Intrusion – AASHTO T 259/260

AASTHO T 259 (2004) is a test method which covers the determination of the resistance of concrete specimens to chloride ion penetration. The method can be used to establish the effects of variations in the properties of concrete on the resistance of the concrete to penetration of chloride ions. Possible variations in the concrete outlined in the standard include the cement and aggregate type and content, water-cement ratio, admixtures, *treatments*, curing conditions, and consolidation.

The standard describes procedures for preparing the concrete test specimens, including the application of concrete sealants. After concrete treatments are applied, specimens are abraded to simulate wear from vehicular traffic. If the concrete or treatment is to be used on surface not subjected to traffic wear, abrasion is omitted. Dams are placed around the top edge of the specimens, before beginning 90 days of continuous ponding of a deicing solution. Following ponding, the specimens are wire brushed to remove any salt crystal buildup.

The AASHTO T 260 (2004) test method describes procedures used to determine the water-soluble or acid soluble chloride ion content of aggregates, cement, mortar, or concrete. In this test, the chloride ion content can be determined by three distinct methods: potentiometric titration (which was used in this test program), atomic absorption, and specific ion probe-field. All three methods require the use of an ion-selective electrode. In addition, the standard presents the procedures for the preparation of powdered concrete samples for determination of the chloride ion content, including sample digestion and dilution. Equations for calculating the percent chloride ion and precision statements are also included. A detailed description of the AASHTO T 259 and T 260 test methods is given later in section 4.4 of this report.

2.3.2 Rapid Permeability – ASTM C 1202

An indirect method used to measure the permeability of concrete is ASTM C 1202 "Standard Tests Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration" (2004). This method is applicable to types of concrete where correlations exist between the results of this test and the long term ponding procedures, such as AASHTO T 259. The test consists of monitoring the amount of electrical current passed through 2 in. thick slices of 4 in. diameter concrete cores or cylinders throughout a 6 hour period. The total charge passed, in coulombs, has been found to be related to the resistance of the specimen to chloride ion penetration. Care should be taken, however, when interpreting the results of this test when it is used on surface treated concretes. ASTM C 1202 has been found to indicate low resistance to chloride ion penetration for concrete treated with penetrating sealers compared to results from longer ponding tests (ASTM 1202, 2004).

2.3.3 Bond Strength of Crack Sealants

There are no standard methods for determining the bond strength of crack sealants. Here, the common splitting cylinder test to measure the tensile strength of the concrete is used to obtain a relative comparison of the bond strength of crack sealants. The ASTM C 496 test method (2004) is commonly used to determine the splitting tensile strength of cylindrical concrete specimens. The test consists of applying two opposing compressive line loads perpendicularly to the axis of a cylinder at a rate within an allowed range until failure occurs. Plywood bearing strips are used to ensure the load is applied uniformly along the length of the cylinder. The loading induces tensile stresses in the plane through which load is applied, and fairly high compressive stresses in the area closely surrounding the applied load, as shown in Figure 2.3.1. Tension failure occurs rather than compressive failure because the area immediately surrounding load application is in a state of triaxial compression, allowing it to resist much higher compressive stresses than would be predicted by a uniaxial compressive strength test. The maximum load sustained by the specimen is divided by appropriate geometric factors to obtain the splitting tensile strength. In this study, a modified version of the split cylinder test is used to measure the bond strength of the crack sealants, where a specimen with a crack filled with the sealant of interest is tested in a manner similar to that shown in Fig. 2.3.1. The tensile stresses induced along the sealed crack represent a measure of the bond strength of the sealant.

A previous study has shown that the stress distribution for splitting cylinder and splitting prism loading conditions produced essentially a uniform tensile stress across most of the vertical splitting plane (Geissert et al., 1999). The maximum tensile stress varied between the cylindrical and prismatic specimens by less than two percent. Prismatic specimens are easier to fabricate and load, and, therefore, prisms rather than cylinders are used in this study. A complete description of the test procedure employed to measure the bond strength of the crack sealants is presented later in Chapter 5.

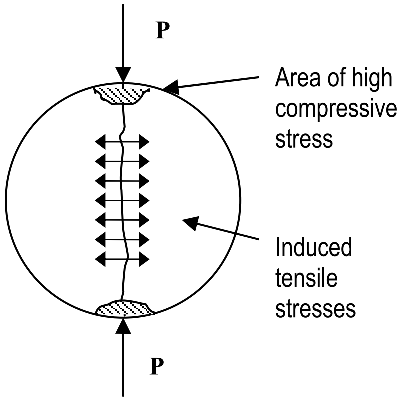


Figure 2.3.1 Stresses induced in a typical cylinder splitting tensile test

2.3.4 Durability Tests

ASTM C 666 — The ASTM C 666 (2004) test method covers the determination of the resistance of concrete specimens to rapidly repeating cycles of freezing and thawing in the laboratory. This test procedure can be used to determine the effects of variations in the properties of concrete to the resistance of concrete to freezing and thawing cycles. However, the test method is not intended to provide a quantitative measure of the length of service that may be expected from a particular type of concrete.

Two procedures can be used: Procedure A, Rapid Freezing and Thawing in Water, and Procedure B, Rapid Freezing in Air and Thawing in Water. Both procedures require that concrete specimens be completely surrounded by water during the thawing phase of the cycles. However, for Procedure B specimens are surrounded only by air during the freezing phase of the cycle, while for Procedure A, specimens are surrounded by water during the freezing phase. Procedure A, Rapid Freezing and Thawing in Water is more severe, since most specimens eventually become fully saturated and fail. Procedure A is better suited for tests relating to concrete bridge decks, since decks will normally be covered with ice (water) while they undergo freezing and thawing. Specimens must be between 3 in. and 5 in. in width, depth or diameter, and between 11 in. and 16 in. in length, and casting and curing procedures must meet specific requirements.

The freeze-thaw cycle regime calls for alternately lowering the temperature of specimens from 40 to 0°F and raising it from 0 to 40°F in not less than two, nor more than five hours. At a regular interval during the tests, specimens are normally removed from the freeze-thaw apparatus and length change is measured and the fundamental transverse frequency is tested. These tests are used to gauge the performance of the concrete due to freeze-thaw cycling. The specimens are continuously subjected to freezing and thawing cycles, until they reach 300 cycles or their relative dynamic modulus of elasticity reaches 60% of the initial modulus, whichever occurs first. The standard provides calculation procedures for determining the relative dynamic modulus of elasticity, length change in percent, and a durability factor.

ASTM C 672 — The ASTM C 672 (2004) test method covers the determination of the resistance to scaling of a horizontal concrete surface exposed to freezing and thawing cycles in the presence of deicing chemicals. This test procedure is intended to be used for evaluating the surface resistance to scaling by visual examination.

Specimens should have a surface area of at least 72 in.^{2} and be at least 3 in. in depth. Also, at least two duplicate specimens should be tested for each combination of variables studied. After completion of the moist and air curing of the concrete, the specimens are covered with approximately ¼ in. of a 4% calcium chloride solution and placed in a freezing environment for 16 to 18 hours. The specimens are then removed from the freezer and placed in an environment at a temperature of 73.5 ± 3.5 °F and a relative humidity of 45 to 55 % for 6 to 8 hours. This freezing and thawing cycle is repeated every day, flushing the surface thoroughly at the end of each 5 cycles to allow visual examination of the surface. The solution is then replaced and the test is continued. According to the standard, 50 cycles are generally sufficient to evaluate the scaling resistance of the surface. However, it is recommended that the tests be continued beyond the minimum number of cycles if differences have not developed when comparative tests are conducted.

Evaluation of scaling resistance is made by visual rating of the surface after 5, 10, 15, 25, and every 25 cycles thereafter using the following scale:

Rating	Condition of Surface
0	No scaling
1	Very slight scaling (⅛ in. depth maximum, no coarse aggregate visible)
2	Slight to moderate scaling
3	Moderate scaling (some coarse aggregate visible)
4	Moderate to severe scaling
5	Severe scaling (coarse aggregate visible over entire surface)

2.3.5 Depth of Penetration – OHD L-40

OHD L-40 is a test method used by the Oklahoma Department of Transportation for determining depth of penetration of penetrating water repellent treatment solutions into Portland cement concrete (OK DOT, 2003). Specimens used in this test procedure are 4 in. diameter cores approximately 4 in. in length retrieved from a concrete surface that has been treated with a penetrating water repellent solution. The cores are split through the sealed surface and immersed in a solution of Sulfonazo III and water, which is capable of staining only the untreated concrete. The cores are then rinsed with water and photographed, and the area of penetration is outlined. Using the specimen width and scale of the photograph, the average depth of penetration is calculated.

2.4 Previous Studies

Several studies have been conducted to evaluate the performance of concrete treated with water repellent deck sealers. The earliest study was organized under the National Cooperative Highway Research Program (NCHRP) which resulted in guidelines on the use of concrete sealants (Pfeifer and Scali, 1981). This study provided a foundation for other water repellent studies (Bradbury and Chojnacki, 1985; Carter and Forbes, 1986) performed in the 1980s. A more recent study performed at the University of Oklahoma in 1998 compared the AASHTO T 259 test procedure with some procedures used in the NCHRP study (Bush, 1998).

Research in the area of concrete crack sealers is very limited. Cracking repair trials performed for the Iowa Department of Transportation qualitatively measured the penetration of sealants into cracks, but there has not been any research done to measure the bond strength and durability of concrete crack sealants. The following sections highlight some of the studies performed to evaluate concrete deck and crack sealants, and the specific areas most relevant to this research.

2.4.1 Concrete Sealers for Bridge Structures – NCHRP Report 244

In this study, the effectiveness of sealers used to protect concrete bridges exposed to chloride contamination was assessed. The study excluded, however, bridge decks exposed to vehicle abrasion. Several of the most commonly used sealant materials at the time, including both penetrating sealants and coatings, were evaluated. Some of the products included in the study were silanes, siloxanes, epoxies, urethanes, methacrylates, and boiled linseed oil, among others.

Four different series of tests were performed on selected materials. Series I was used as a screening test to evaluate the water absorption and chloride ion intrusion reduction for the 21 selected products. Concrete cubes were lightly sandblasted then sealed with one of the selected materials and immersed in a 15 percent sodium chloride solution for 21 days. Cubes were removed periodically to determine weight gain and, at the end of immersion period, split in half. One half of each cube was tested for the total chloride ion content using acid digestion and potentiometric titration. Five products exhibiting good performance in the Series I tests were selected for further testing in Series II, III and IV.

Series II tests were used to study the effect of moisture content at the time of application of the sealant, while Series III tests were used to evaluate the effect of coverage rate on the chloride intrusion characteristics. Both Series II and III used the same 21 day immersion procedure used in Series I.

Series IV tests studied the performance of the five selected materials when subjected to 24 weeks of accelerated laboratory weathering. Two accelerated weathering procedures were used. One procedure was used to simulate a southern climate by immersing specimens in a 15 percent sodium chloride solution, then removing and exposing them to ultraviolet light and infrared heat. The other procedure was meant to simulate a northern climate by exposing specimens to a wide range of environmental conditions which included acid and saltwater exposure, and overnight freezing and thawing cycles.

The NCHRP study found that good performance in Series I tests did not necessarily predict good performance in Series II, III and IV tests. Only three materials, an epoxy, a methacrylate and a silane provided good performance throughout all series tests. Additionally, the silane appeared to be the only true “penetrating sealant” included in the study, which was able to provide a water repellent surface to a depth of about 0.10 in. Still, the acid exposure included in Series IV tests caused etching of the concrete surface and removal of up to 0.125 inches of material, which created significant long-term performance problems for even the silane penetrating sealant (Pfiefer and Scali, 1981).

The results of the NCHRP study provide insight into the performance of a range of sealant products exposed to varying conditions on non-wearing bridge surfaces. As the objective of this research project was to evaluate concrete bridge deck sealants, AASHTO T 259 is a more appropriate test method than the method used throughout the NCHRP study, since AASHTO T 259 includes surface abrasion when concrete surfaces or sealants will be subjected to traffic. Furthermore, although the products used in the NCHRP study were broadly classified, specific product formulations were used. Thus, their test results are formulation specific that cannot be extended to an entire generic classification of products.

2.4.2 Comparison of NCHRP 244 procedures and AASHTO T 259 test

The performance of a single silane sealer was examined at the University of Oklahoma using two different test series; one specified by the Oklahoma DOT, the other based on Series II tests procedure of the NCHRP Report 244. The objective of the study was to compare the results of water absorption, chloride ion penetration and depth of penetration using the two different test series.

The Oklahoma DOT series tests included absorption and chloride ion intrusion tests which followed established ASTM and AASHTO standards, while the depth of penetration test was developed by the Oklahoma DOT. Depth of penetration specimens were wet cured for one week, then oven dried to constant weight. Silane was applied to the test surface and allowed to cure. Following curing, the block was broken into four pieces, each rewetted and the visible depth of hydrophobic layer measured at 12 random locations. The depths were averaged and reported as the penetration depth.

Specimens used to measure absorption were wet cured for 28 days then oven dried to constant weight. Silane was applied to the top surface and all other surfaces were waxed to force all absorption to occur through the silane-treated surface. Absorption was measured after 48 hour and 50 day immersion in water for both treated and untreated specimens.

Chloride ion intrusion was measured using AASHTO T 259 and T 260, and did not include the surface abrasion. Blocks were wet cured for 14 days, followed by curing in an environmental chamber for an additional 14 days. Silane was applied to the specimens after one week of air curing. Ninety day continuous ponding of the top surface of the specimen began after two additional weeks of drying. At the conclusion of ponding, powder samples were drilled at two depths using a rotary hammer, 1/16 in. to ½ in., and ½ in. to 1 in. Chloride ion analysis was performed and the total absorbed chloride was determined.

The basic test procedures of NCHRP Series II tests were used. Concrete cubes were cured in plastic bags for 21 days, followed by five days in an environmental chamber. The cubes were lightly sandblasted at seven days of age to remove surface buildup. Specimens were treated with silane and allowed to dry in the environmental chamber for an additional 26 days, before being immersed for 21 days in a 15 percent sodium chloride solution. Weight measurements were taken throughout immersion and an additional 21 days of drying following immersion. Measurements of chloride ion content for the NCHRP cubes were obtained using drilled powder samples as in the AASHTO T 259 test, rather than by crushing which was done in the original NCHRP tests. Both the DOT series of tests and the NCHRP series tests were performed on three types of concrete mixes, each using a different water-cement ratio.

The University of Oklahoma study found that sealant penetration was smaller for concrete tested with NCHRP Series II tests than for the Oklahoma DOT test method. For concrete mixes with three different water-cement ratios, absorption trends were different for the two test series. Absorption decreased by the DOT test method as water-cement ratio decreased, while the results of the NCHRP series test showed that the highest absorption occurred in the mix with the intermediate water-cement ratio.

Chloride ion content was similar for the two test series despite the different salt concentration and immersion time for the two test series. Converted to pounds of chloride per cubic yard of concrete, absorbed chloride ion content ranged from 0 pounds per cubic yard for a treated sample to 5.13 pounds per cubic yard for an untreated sample. The scatter in nearly all the chloride results was, however, quite large with the standard deviation nearly equal to or even larger than the mean in most cases.

Overall, the study demonstrated that different tests examining the same parameter do not necessarily yield the same results. The University of Oklahoma study did not include freeze-thaw cycle tests or surface abrasion to simulate traffic wear, and therefore caution must be used when comparing the results of the University of Oklahoma study with other studies.

2.4.3 City Island Bridge crack analysis and repair trials

Crack analysis and repair trials were performed on the City Island Bridge over the Mississippi River for the Iowa DOT in 1999. Cores were removed by the Iowa DOT and provided to Wiss, Janney, Elstner Associates, Inc. (WJE). The cores were examined and the quality of the deck concrete and characteristics of the cracks were noted. In addition, chloride ion tests were performed to investigate the depth of chloride ion penetration.

Two attempts were made to repair and seal cracks in the bridge deck. Products used in the repair attempt were selected based on the characteristics of the cracks and the large number of cracks in the deck. The cracks included in that study ranged from 0.3 to 0.7 mm (0.004 to 0.010 in) wide. Three high molecular weight methacrylate (HMWM) resins, one epoxy resin, and one urethane resin overlay were used in the first repair trial. Each product was applied to a section of the cracked bridge which was lightly sandblasted and cleaned with compressed air. WJE removed cores from the application sites one week later, which were sliced and polished to assess the depth of penetration of the sealant materials. The depth of penetration of the sealant materials ranged from 1 to 8 mm, which researchers concluded was inadequate to bond the cracks together.

Epoxies, HMWMs, silanes and combinations of products were selected for the second repair trial. Additional cracked deck sections were selected to receive the sealant materials, and cracks were water jetted before the sealants were applied. WJE personnel returned and removed core samples from the test sections one week later. The core samples were again sliced and assessed for depth of penetration. The depth of penetration of the sealant materials used in the second trial ranged from 2 to 55 mm.

The researchers concluded the HMWM and epoxy resins were unable to penetrate cracks adequately to structurally bond the cracks. They concluded that the cracks were filled with an extensive amount of dirt and debris, which appeared to inhibit penetration of the HMWM and epoxies selected for evaluation. Silanes and overlay systems however, appeared viable to seal cracks and extend the service life of a crack. Silanes were able to penetrate and coat the inside of cracks, providing a hydrophobic layer to depths between 35 and 55 mm (Krauss and Boyd, 1999). The researchers acknowledged, however, that it is unknown whether silanes can effectively prevent water infiltration into cracks when subjected to truck traffic service loads and bridge deflections. The bond strength of the sealants was not tested, and the impact of freeze-thaw cycles on the performance of the crack sealants was not evaluated. Furthermore different product formulations may provide different results, particularly when a larger range of crack widths is considered. The products included in that study should not be used to make general statements about the behavior of a generic product category.

Chapter 3

Identification, Review, and Selection of Deck and Crack Sealants

3.1 Introduction

In this chapter, the process to identify potential deck and crack sealants for evaluation in this study is presented. Based on feedback from WisDOT District Bridge Maintenance Engineers and manufacturer product data, the identified products are reviewed and ranked in terms of their expected performance. The chapter concludes with a summary of the deck and crack sealers selected for testing in consultation with the Project Oversight Committee.

3.2 Identification of Potential Products

A variety of methods were used to identify potential deck and crack sealant products. The methods used to identify potential products were as follows:

- Deck sealant products currently approved for use by the WisDOT were first identified.
- A survey was sent to Bridge Maintenance Engineers to identify other deck and crack sealant products being used by the Districts.
- A Structures Maintenance webpage maintained by the WisDOT on the use and reported comments of several other deck and crack sealant products.
- Internet searches.

The above methods helped to identify nearly 40 potential products as described in the following sections.

3.2.1 Wisconsin DOT approved products

The WisDOT provided a list of concrete protective surface treatments, which were tested at the WisDOT Materials Laboratory and approved for use on concrete bridge decks. The products on the approved list are subjected to the AASHTO T 259 test procedure to prepare the specimens (see section 2.3.1) and to the ASTM C672 Standard (see section

2.3.4). To perform chloride ion analysis of the samples, the test method described in Federal Highway Administration (FHWA) RD-72-12, "Determination of Chloride in Hardened Portland Cement Paste, Mortar, and Concrete" was used (Berman, 1972). This procedure allowed for the development and acceptance of the standard AASHTO T 260 test method used today to measure the total chloride ion content in concrete.

The acceptance criterion for penetrating sealants used by the WisDOT is based on a ratio between the absorbed chloride of sealed versus unsealed specimens. A penetrating sealant is considered to be approved if the averaged absorbed chloride ion content of a sealed specimen is reduced by one half with respect to that of an unsealed specimen from the same batch of concrete. Thus, the WisDOT acceptance criterion for penetrating sealants is given by the following equation:

$$Cl^{-}_{sealed} \leq \left(\frac{Cl^{-}_{unsealed} - Cl^{-}_{control}}{2} \right) + Cl^{-}_{control} \qquad \textbf{(3-1)}$$

where

Cl^{-}_{sealed} = average total chloride ion content of a ponded, sealed specimen
$Cl^{-}_{unsealed}$ = average total chloride ion content of a ponded, unsealed specimen
$Cl^{-}_{control}$ = average baseline chloride ion content of a control specimen, unponded and unsealed

The above equation can be rewritten as:

$$Cl^{WisDOT}_{content} \equiv \frac{Cl^{-}_{sealed}}{Cl^{-}_{unsealed} + Cl^{-}_{control}} \leq 0.5 \qquad \textbf{(3-2)}$$

The left side of equation (3-2) may be called the "chloride content ratio," $Cl^{WisDOT}_{content}$.

In addition to the above requirements, the scaling resistance of the surface of specimens treated with the sealants is rated according to the ASTM C672 Standard (2004). A penetrating sealant is considered to be approved if the test block is rated at least on full visual rating unit better than the control blocks, and in no case shall exceed a rating of 2.

The current WisDOT approved list of concrete protective surface treatments, product manufacturers and approval dates are shown in Table 3.2.1.

3.2.2 District bridge engineer product survey and results

After reviewing the sealants on the WisDOT list of approved products, an internet search was conducted to identify other potential products suitable for concrete bridge decks. Additionally, information on the field performance of products used by districts was reported on a Structures Maintenance webpage maintained by Fred Wisner at the WisDOT. Once additional products were identified, a survey was sent to bridge maintenance engineers in all Districts in Wisconsin. The goal of the survey was to supplement the information on the Structures Maintenance webpage by learning about districts' experience using concrete bridge deck and crack sealants, and learn of any other products that the Districts were using or had used in the past. The survey consisted of questions about the use of approved and other products on both new and existing bridge decks, including the frequency and ease of application and the overall performance of the product. A copy of the survey sent to District Bridge Maintenance Engineers is given in Appendix A.

Table 3.2.1 WisDOT approved concrete protective surface treatments

	Product Name	Manufacturer	Date Approved
1	Aqua-Trete BSM 20	Degussa, Inc	3/16/2001
2	Baracade WB 244		** Pre-1999
3	Penseal 244 40%	Vexcon Chemical	** Pre-1999
4	Eucoguard 100		** Pre-1999
5	Hydrozo Enviroseal 20	ChemRex, Inc.	** Pre-1999
6	Hydrozo Enviroseal 40	ChemRex, Inc.	** Pre-1999
7	Hydrozo Silane 40 VOC	ChemRex, Inc.	3/16/2001
8	Masterseal SL 40 VOC	ChemRex, Inc.	12/30/2002
9	NitecoteDekguard P-40		** Pre-1999
10	Spall-Guard 40	Chemmasters	3/16/2001
11	TK-290-WDOT (or TK-290-16)	TK Products	** Pre-1999
12	TK-290-WDOT E	TK Products	3/16/2001
13	TK-290-WBG	TK Products	3/16/2001
14	Powerseal 40%	Vexcon Chemical	** Pre-1999
15	Sonneborn Penetrating Sealer 40 VOC	ChemRex, Inc.	12/30/2002

A summary of the responses from the District Bridge Maintenance Engineer survey is given in Table 3.2.2. The results from the survey showed that the TK-290-WDOT and TK-290-WDOT E were the only products from the approved list of products being used by the Districts. Other products used by the Districts included: TK-9000 (crack sealer), 10 Minute Concrete Mender (patch material), TK-26 (coating for non-trafficked surfaces), V-Seal and Star Macro-Deck (deck sealers not previously tested by the WisDOT).

Based on the list of approved products, maintenance webpage information, district survey results, and internet searches the products listed in Table 3.2.3 were identified as potential products and included in preliminary review.

3.3 Product Evaluation Based on Manufacturer Product Data

The products included in the preliminary review were categorized, evaluated and ranked based on the characteristics of sealants described in section 2.2. The information obtained in the preliminary review was used to identify products with the potential to perform well, and eliminate products which were unsuitable for use on bridge decks in Wisconsin.

3.3.1 Product Composite Score

The characteristics of the potential products listed in Table 3.2.3 were recorded and divided into the following categories: surface preparation requirements, environmental application conditions, expected durability, time to open traffic, coverage rate and cost, and freeze-thaw resistance (i.e., whether or not a product was suitable for Wisconsin environmental conditions). If a product was deemed unsuitable for Wisconsin conditions, it was eliminated from the list of potential products. Duplicate and discontinued products were also removed from the list, along with products unsuitable for surfaces subjected to vehicular abrasion. Concrete patch and repair materials were also eliminated. Lastly, feedback from the District Bridge Maintenance Engineers revealed that crack sealants requiring pressure injection application were undesirable, so products requiring pressure application were also removed from the list of potential products.

Table 3.2.2 Summary of survey responses from District Bridge Maintenance Engineers

		WisDOT District																	
		1		2	3			4	5		6				7		8****		
		TK-290-WDOT (or TK-290-16)	10 Minute Concrete Mender		TK-290-WDOT (or TK-290-16)	TK-9000	TK-26	TK-290-WDOT *****	TK-290-WDOT E	V-Seal***	TK-9000	10 Minute Concrete Mender	Star-Macro Deck	TK-290-WDOT (or TK-290-16)	TK-290	TK-26	TK-290 ?	TK-9000	10 Minute Concrete Mender
	General			Has not used any of the products listed in the survey.															
1.	How long have you been specifying this product? (Leave blank if not used.)														**				
	a.) 1 year or less													X					
	b.) 1-5 years		X			X			X	X	X	X	X				X	X	X
	c.) more than 5 years	X			X		X	X											
2.	Please indicate the ease of application of this product:																		
	a.) easy and quick to apply	X			X			X				X	X				X		X
	b.) moderately difficult and time consuming to apply					X	X		X									X	
	c.) very difficult and time consuming to apply										X			X					
	Durability & Performance of Product																		
3.	On average, how often does the product need to be applied to the same surface?																		
	a.) every 1 year																		
	b.) every 2 years										X	X							
	c.) every 5 years				X	X	X		X					X				X	X
	d.) every 10 years																		
	e.) other, please specify ___________________________	*						3 yr									3 yr		
4.	For **NEW DECKS** subjected to similar traffic and environmental conditions, the product:																		
	a.) delayed deterioration since application of the product				X	X	X		X		X	X						X	X
	b.) resulted in no visible change since application of the product							X									X		
	c.) increased the rate of deterioration since application of the product																		
5.	For **EXISTING DECKS** subjected to similar traffic and environmental conditions, the product:																		
	a.) delayed deterioration since application of the product				X	X	X		X		X	X		X				X	X
	b.) resulted in no visible change since application of the product							X									X		
	c.) increased the rate of deterioration since application of the product																		

Table 3.2.2 Summary of the survey responses from District Bridge Maintenance Engineers (Continued)

Additional Comments	
*	District 1 has not reapplied the TK-290 WDOT sealer; has not developed an opinion on 10 Minute Concrete Mender yet
**	District 7 Bridge Maintenance Engineer took over about 1 year ago – he has little experience with the long term performance of deck and crack sealers. Only knows the products most used by the district.
?	Used one formulation of TK-290, most likely TK-290 WDOT
***	District 5: As of now it is not on WisDOT approved materials list. It has been used on a few bridges for maintenance and trial/testing purposes. Our Central Office in Madison is testing this product. Determination of its acceptance should be known later this summer.
****	District 8: We've switched from the TK-9000 to the 10 Minute Concrete Mender just because of the ease of application. It really speeded things up.
*****	District 4: I have been using TK-290 for 7-8 years as a preventive maintenance treatment for existing bridge decks. On average, I schedule resealing on a 3 year rotation. Manufacturers product data says to reseal every 7 years. However, we use approximately 1/2 the manufacturers application rate when we reseal (because time to re-open traffic is reduced) and reseal twice as often. All bridges that have their decks in good condition receive this treatment. Typically these are bridge decks less than +/- 20 years old. In conjunction with the deck sealing operations, crews seal bridge deck cracks. I have been using TK-290 almost exclusively for 7-8 years. 2003 cost is +/- $12/gal. Application rate we use is +/- 250-300 sq. ft./gal. Product is applied with a 12 volt drum sprayer which is quite efficient. Disadvantage of product is it has high VOC content. Crews use respirators (at their option) when applying products. Generally, no complaints are received.

Table 3.2.3 Potential products included in the preliminary review

	Product Name	Manufacturer	Source
1	10 Minute Concrete Mender	Roadware, Inc.	Structures Maintenance webpage and District survey
2	Aquanil Plus 40 (previously Spall-Guard 40)	Chemmasters	Approved list
3	Aqua-Trete BSM 20	Degussa, Inc	Approved list
4	Baracade WB 244	Tamms Industries	Approved list
5	Degadeck Crack Sealer	Degussa, Inc	Internet search
6	Denedeck Crack Sealer	DeNeef Construction Chem.	Internet search
7	Denepox 1-60	DeNeef Construction Chem.	Internet search
8	Denepox I-40	DeNeef Construction Chem.	Structures Maintenance webpage
9	Duraguard 100	Chemmasters	Internet search
10	Duraguard 401	Chemmasters	Internet search
11	Dural 335	Tamms Industries	Internet search
12	Duralcrete LV	Tamms Industries	Internet search
13	Eucoguard 100	Euclid Chemical Company	Approved list
14	Eucopoxy Injection Resin	Euclid Chemical Company	Internet search
15	Hydrozo Enviroseal 20	ChemRex, Inc.	Approved list
16	Hydrozo Enviroseal 40	ChemRex, Inc.	Approved list
17	Hydrozo Silane 40 VOC	ChemRex, Inc.	Approved list
18	Masterseal SL 40 VOC	ChemRex, Inc.	Approved list
19	NitecoteDekguard P-40	Fosroc	Approved list
20	Penseal 244 40%	Vexcon Chemical	Approved list
21	Powerseal 40%	Vexcon Chemical	Approved list
22	Sikadur 52	Sika USA	Internet search
23	Sikadur 55 SLV	Sika USA	Internet search
24	SikaPronto 19	Sika USA	Internet search
25	Sonneborn Penetrating Sealer 40 VOC	ChemRex, Inc.	Approved list
26	Star-Macro Deck	STAR, Inc.	District survey
27	TK 9000	TK Products	Structure Maintenance webpage and District survey
28	TK 9010	TK Products	Internet search
29	TK 9030	TK Products	Internet search
30	TK-26 - Gray Pigmented	TK Products	Structures Maintenance webpage and District Survey
31	TK-2671	TK Products	Internet search
32	TK-290-WBG	TK Products	Approved list
33	TK-290-WDOT (or TK-290-16)	TK Products	Approved list
34	TK-290-WDOT E	TK Products	Approved list
35	TK-9020	TK Products	Internet search
36	V-Seal	TARA Distribution Group	District survey

The remaining deck and crack sealants, and product manufacturers are shown in Table 3.3.1. The products were assigned a score between 1 and 10 in each of the above categories, with 10 representing the most desirable quality. Initially, the score in each category was weighed equally. After further consideration and discussion with the District

Bridge Maintenance Engineers and the POC, the assigned score was weighed differently according to the relative importance of each category. Less important characteristics were weighed less, while the more important attributes were weighed more. Accordingly, surface preparation requirements, application conditions, and coverage rate and cost were all given a weight of 1. Expected durability was given a weight of 2, and time to open traffic (the most important attribute) was given a weight of 3.

Table 3.3.1 Potential deck and crack sealant products after preliminary evaluation

	DECK SEALANTS	
	Product Name	**Manufacturer**
1	Aquanil Plus 40	Chemmasters
2	Aqua-Trete BSM 20	Degussa, Inc.
3	TK-290 Tri-Siloxane	TK Products
4	TK-290 WB Tri-Siloxane	TK Products
5	Penseal 244 40%	Vexcon Chemical
6	Powerseal 40%	Vexcon Chemical
7	Baracade WB 244	Tamms Industries
8	Sonneborn Penetrating Sealer 40 VOC	ChemRex, Inc.
9	Hydrozo Enviroseal 20	Chemrex, Inc.
10	Hydrozo Enviroseal 40	Chemrex, Inc.
11	V-Seal	Tara Distribution Group
12	Hydrozo Silane 40 VOC	Chemrex, Inc.
13	Euco-guard 100	Euclid Chemical Company
	CRACK SEALANTS	
1	Degadeck Crack Sealer	Degussa, Inc.
2	TK-9010 Crack & Joint Repair	TK Products
3	TK-9000	TK Products
4	TK-9030 Crack & Joint Repair	TK Products
5	Denedeck Crack Sealer	DeNeef Const. Chem.
6	Sikadur 55SLV	Sika USA
7	Dural 335	Tamms Industries
8	Duraguard 401	Chemmasters
9	SikaPronto 19	Sika USA
10	Sikadur 52	Sika USA

Using this point system, each product was assigned a composite score. The maximum composite score that a given product could attain was 80, while the minimum was 8. Clearly, products with the highest composite score would display the best combination of desirable traits. Table 3.3.2 shows the thirteen deck sealant products, the review categories and scores, and the product composite score. Table 3.3.3 displays similar information for the ten crack sealants listed in Table 3.3.1.

3.4 Products Selected for Testing

The calculated composite score for the deck sealants ranged from as low 28 to as high as 58, with most sealants having a score in the 40 to 50 range (see Table 3.3.2). In other words, there were no sealants that clearly surpassed or were inferior to the rest (except Eucoguard 100 with a composite score of 28). After consultation with the Project Oversight Committee (POC), all thirteen deck sealants listed in Table 3.3.2 were selected to undergo testing.

The composite score computed for the crack sealants ranged from 38 to 71, with most products having a score in the 50 to 70 range (see Table 3.3.3). Only two products (Sikadur 52 and SikaPronto 19) had a lower score. Based on these results, the authors in consultation with the POC agreed to select all ten crack sealants for testing.

Table 3.3.2 Deck sealant properties, category scores and composite scores

Rank	**Product Name**	**Chemical Family**	**VOC Content**	**Manufacturer Reported Depth of Penetration**	**Surface Preparation Requirements**	*Score*	**Application Conditions**	*Score*	**Coverage Rate & Cost**	*Score*	**Expected Durability**	*Score*	**Time to Open Traffic**	*Score*	**Environmental Conditions**	**Composite Score**
1	Aquanil Plus 40 (prev. SpallGuard 40)	silane, solvent-based	less than 350 g/L	unknown	clean and dry, powerwash min pressure of 2500 psi	3	40<T<100 F, do not use if rain within 4 hrs	6	100-150 sf/gal; $28/gal	1	10 year max life	9	1-2 hrs	10	developed to protect in freeze/thaw conditions	58
2	V-Seal 102-V4	siliconate	0 g/L	0.75-1.0 inch	clean, powerwash suggested	5	T>35 F, do not use if rain within 5 hrs	6	150-200 sf/gal; $12/gal	10	5 years	4	2-4 hrs	9	superb for freeze-thaw climates	56
3	Aqua-Trete BSM 20	silane, water-based	350 g/L	0.125-0.25 inch	clean all traces of dirt, dust, by shotblasting, sandblasting, waterblasting, and chemical cleaners	1	40<T<100 F do not use if T<40 within 12 hrs, or precipitation expected within 4 hrs	4	125-175 sf/gal; $15/gal	8	bridge decks 5-7 yrs	5	when visibly dry - usually 2 hrs at 70 F and <80% RH	10	New York DOT uses this - resists freeze/thaw	53
4	TK-290 Tri-Siloxane (or TK-290-WDOT)	siloxane, solvent-based	741 g/L	0.125-0.25 inch	sound, dry, cleaned thoroughly, may need mech. abrasion to get max penetration	3	T>40 F, do not use if rain within 4-6 hrs	5	100-175 sf/gal on bridge decks; $13/gal	9	5 years excellent 10-15 yr-depends on traffic	6	4 hrs	8	unaffected by freeze-thaw conditions	53
5	TK-290 WB Tri-Siloxane (or TK-290-WBG)	siloxane, water-based	140 g/L	0.125-0.25 inch	sound, dry, cleaned thoroughly, may need mech. abrasion to get max penetration	3	T>40 F, do not use if rain within 4-6 hrs	5	100-200 sf/gal on bridge decks; $15/gal	8	5 years excellent 10-15 yr-depends on traffic	6	4 hrs	8	unaffected by freeze-thaw conditions	52

Table 3.3.2 Deck sealant properties, category scores and composite scores (Continued)

Rank	Product Name	Chemical Family	VOC Content	Manufacturer Reported Depth of Penetration	Surface Preparation Requirements	Score	Application Conditions	Score	Coverage Rate & Cost	Score	Expected Durability	Score	Time to Open Traffic	Score	Environmental Conditions	Composite Score
6	Baracade WB 244	siloxane/ silane oligomers water-based	50 g/L	0.375 inch	clean, dry, structurally sound; pressure washing works well, sandblasting ususally not required	3	T>40 F, do not use if rain within 12 hrs	4	100-150 sf/gal; $20-24/gal	3	10 yrs under heavy traffic	9	4-6 hrs for T~70's F	7	very effective in climates with drastic temp. if used correctly	49
7	Penseal 244 40%	silane, solvent-based	496 g/L	0.125-0.25 inch	Older concrete - power washed with cleaners to remove contaminants; may be damp but absorbent for good penetration.	5	T>20 F, protect from rain and foot traffic for 4-6 hrs	6	125-250 sf/gal, Older: 95-140 sf/gal; $23/gal	7	10 years	9	8 hrs	4	effective in freeze-thaw conditions	48
8	Hydrozo Enviroseal 20	silane, water-based	399 g/L	0.14 inch	clean, sound, and dry for best performance; may need to sandblast, shotblast	3	T>40 F, do not use if T<40 or inclement weather within 12 hrs.	4	100-175 sf/gal; $20/gal	5	5-7 yrs; still some protection after 10-15 yrs	7	dry in 4-6 hrs @ 70 deg F	7	unaffected by freeze-thaw as long as concrete isn't	47
9	Powerseal 40%	silane, water-based	260 g/L	0.125-0.25 inch	Older concrete - power washed with cleaners to remove contaminants; may be damp but absorbent for good penetration.	5	Protect from rain for 4-6 hrs, T>40 F	5	125-250 sf/gal, Older: 95-140 sf/gal; $23/gal	7	10 years	9	8 hrs	4	effective in freeze-thaw conditions	47

Table 3.3.2 Deck sealant properties, category scores and composite scores (Continued)

Rank	**Product Name**	**Chemical Family**	**VOC Content**	**Manufacturer Reported Depth of Penetration**	**Surface Preparation Requirements**	*Score*	**Application Conditions**	*Score*	**Coverage Rate & Cost**	*Score*	**Expected Durability**	*Score*	**Time to Open Traffic**	*Score*	**Environmental Conditions**	**Composite Score**
10	Sonneborn Penetrating Sealer 40 VOC	silane, solvent-based	589 g/L	0.2 inch	must be clean, dry and structurally sound	3	20<T<95 F, do not use if T<20 within 12 hrs, or rain within 4 hrs	5	125-250 sf/gal; $30/gal	4	5-7 yrs	5	as soon visibly dry (4 hrs)	8	unaffected by freeze-thaw as long as concrete isn't	46
11	Hydrozo Silane 40 VOC (same as Masterseal SL40 VOC)	silane, solvent-based	589 g/L	0.2 inch	must be clean, may need to sandblast, shotblast; may be slightly damp	5	T>40 F, do not use if T<20 within 12 hrs, rain within 4 hrs, or inclement weather within 12-24 hrs	3	125-225 sf/gal; $30/gal	4	5-7 yrs	5	dry in 4-6 hrs @ 70 F	7	unaffected by freeze-thaw as long as concrete isn't	43
12	Hydrozo Enviroseal 40	silane, water-based	399 g/L	0.24 inch	clean, sound, and dry for best performance; may need to sandblast, shotblast	3	40<T<110 F, do not use if T<40 or inclement weather within 12 hrs.	4	100-200 sf/gal; $27/gal	3	5-7 yrs	5	dry in 4-6 hrs @ 70 deg F	7	unaffected by freeze-thaw as long as concrete isn't	41
13	Eucoguard 100	siloxane, solvent-based	723 g/L	0.3-0.4 inch	dry for 24 hrs, pressure wash with water or other cleaners where appropriate	3	T>40 F	8	125 sf/gal; $20/gal	4	5-7 yrs before re-application	5	10-12 hrs	1	unaffected by freeze-thaw	28

Table 3.3.3 Crack sealant properties, category scores and composite scores

Rank	Product Name	Chemical Family	VOC Content	Crack Width	Surface Preparation Requirements	*Score*	Application Conditions	*Score*	Expected Durability	*Score*	Time to Open Traffic	*Score*	Cost	*Score*	Environmental Conditions	Composite Score
1	Degadeck Crack Sealer	Metha-crylate	150 g/L	hairline - 0.125"	cleaned by mechanical means, dry	4	40<T<100 F	8	should last life of the structure	10	35-45 min	10	$30-40/gal	9	effective in freeze-thaw conditions	71
2	Denedeck Crack Sealer	Methacrylate	100 g/L	hairline - 0.125"	cleaned by mechanical means, sound, and nearly dry	5	14<T<104 F	9	25-30 yrs, will depend on service conditions	10	45 min - 1 hour	10	$75/ gal	7	effective in freeze-thaw conditions	71
3	Duraguard 401	HMWM	0 g/L	0.001 and larger	cleaned by mechanical means, structurally sound, visibly dry	4	40<T<120 F, do not use if rain within 12 hrs or previous 24 hrs	8	depend on amount of traffic wear, material in crack should last the life of the structure	10	2 hrs	8	$55/ gal	8	would be suitable for WI-type conditions	64
4	TK-9010	Epoxy	0.6 g/L	up to 0.125"	cracks must be clean, moisture tolerant	7	good adhesion to damp concrete, flexible, low temp application	8	10-20 years	9	tack free in 1 hour	10	$31/ 22 oz. or $180/gal	1	material in crack unaffected by freeze thaw	64
5	TK-9030	Urethane Polyurea Hybrid	423 g/L	up to 0.125"	cracks must be clean and dry	4	dry, flexible, low temp. application	8	10-20 years	9	tack free 1 hour	10	$22/22 oz. or $128/ gal	4	unaffected by freeze thaw	64

Table 3.3.3 Crack sealant properties, category scores and composite scores (Continued)

Rank	Product Name	Chemical Family	VOC Content	Crack Width	Surface Preparation Requirements	Score	Application Conditions	Score	Expected Durability	Score	Time to Open Traffic	Score	Cost	Score	Environmental Conditions	Composite Score
6	TK-9000	Epoxy	<400 g/L	0.0625" and larger	must be clean and dry	4	T>40 F	8	material penetrating crack should last the life of the bridge	10	4 hrs at 70 F	7	$35/ gal	9	unaffected by freeze thaw	62
7	Sikadur 55SLV	Epoxy resin	112 g/L	0.004 - 0.25"	cleaned by mechanical means, sound, may be damp	6	T>40 F	8	depends highly on degree of deteoriation of the deck ~20 yrs	10	6 hrs	5	$130/ gal	4	unaffected by freeze-thaw	53
8	Dural 335	Epoxy	<10 g/L	hairline cracks	cleaned by mechanical means, sound, and dry	4	50<T<90 F	5	5-15 years	8	4-6 hrs at 75 F	6	$35/ gal	9	used for many years in freeze-thaw conditions	52
9	Sikadur 52	Epoxy	73 g/L	0.0001-0.125"	clean and sound, dry for best performance, but may be damp	6	T>40 F	8	depends highly on degree of deteoriation of the deck ~20 yrs	10	10-12 hrs	1	$100/ gal	6	unaffected by freeze-thaw	43
10	SikaPronto 19	HMWM		hairline - 0.125"	cleaned by mechanical means, sound, may be damp	6	T>35 F	8	depends highly on degree of deteoriation of the deck ~20 yrs	10	12 hrs max	1	$180/ gal	1	unaffected by freeze-thaw	38

Chapter 4

Test Program – Deck Sealants

4.1 Introduction

In this chapter, the test program used in this study to assess the performance of the deck sealants is presented. Test methods and procedures, specimen fabrication and test equipment used are also described in detail.

4.2 Program Overview

The primary objective of this task was to assess the ability of the selected deck sealants to improve the resistance of concrete to the ingress of chloride ions. To accomplish this goal a test procedure based on AASHTO T 259 "Resistance of Concrete to Chloride Ion Penetration" (2004) and AASHTO T260 "Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials" (2004) was employed. Concrete specimens were cast, sealed, sandblasted and ponded with a sodium chloride solution for 90 days. Additional specimens were subjected to freeze-thaw cycles while being ponded to determine the deterioration of the sealants over time in an environment similar to typical Wisconsin winters. After ponding, specimens were allowed to dry and samples were removed and tested for the chloride ion content.

In addition, separate specimens were cast and sealed, but were not sandblasted. These specimens were used to determine the depth of penetration of each sealant using a dye method.

Casting, preparation, and sealing of the concrete specimens, as well as the equipment and procedures used for each test are described in further detail in the following sections.

4.3 Description of Test Specimens

Two sizes of concrete specimens were used to conduct the chloride ion analysis and the depth of penetration tests. The chosen specimen size for the chloride ion analysis was 3 in. by 11 in. by 11 in., while the specimens used for the depth of penetration test measured 3 in. by 4 in. by 16 in. The larger specimen size used for chloride ion analysis was chosen to conform to the requirements of AASHTO T 259. The smaller specimen size chosen for the depth of penetration test provided both a sufficient surface area to apply the sealant (4 in. by 16 in.) which allowed several depth of penetration measurements to be taken from each specimen, and a depth (3 in.) which far exceeded the manufacturer reported depth of penetration of all sealants. In addition, forms were readily available in the WSMTL for both specimen sizes chosen.

4.3.1 Mix design

The concrete mix design was based on the proportions for Grade D concrete as listed in the *State of Wisconsin, Department of Transportation: Standard Specification for Highway and Structure Construction* (1996). Grade D concrete is to be used for concrete masonry in decks, curbs, railings, parapets, medians, and sidewalks of structures. Material quantities for one cubic foot of Grade D concrete as given in the Wisconsin Bridge Manual are given in Table 4.3.1.

Table 4.3.1 Material quantities for Grade D concrete

Grade D Concrete Mix Proportions:	**lb/ft^3 of concrete**
Cement:	
Type I/II Portland Cement	22.6
Aggregate:	
Total Dry Aggregate	112.6
% Sand = 40%	45.0
% #1 Stone = 60%	67.6
Water:	
As needed to achieve 3" +/- 1" slump	
Design	9.0
Max	10.6
Air:	
As needed to achieve 6% +/- 1% air	

In addition, the *Standard Specification* (1996) states that all grades of concrete should contain a water reducing admixture. This was omitted at the suggestion of the POC, as the requirement was new to the standard, and concrete used for similar tests at the WiDOT in previous years didn't contain a water reducing admixture. At the recommendation of the

WisDOT, LaFarge brand Type I/II Portland cement (from Alpena, MI) was used. The sand and stone were provided by local quarries. The cement Sika AER, a vinsol resin manufactured by Sika was used as the air-entraining agent. The Grade D concrete mix design used for bridge decks has a design strength of 4000 psi according to the Wisconsin Bridge Manual. Additionally, members of the WisDOT Materials Laboratory suggested that sufficient strength, workability, and air content would be achieved if the slump was within the range of 3.0 +/- 1 in. and the air content held to 6.0 +/- 1%. A constant water-cement ratio of 0.45 was used throughout all mixes to achieve the necessary parameters.

The concrete required to prepare all specimens used for the chloride ion analysis was cast in 14 batches. Each batch contained enough material to produce ten 3 in. by 11 in. by 11 in specimens. Of the ten specimens in each batch, three were treated with one sealant, three were treated with another sealant, and the remaining four were left unsealed. Three of the four unsealed specimens were ponded along with the sealed specimens, to provide a relative comparison of the performance of sealed versus unsealed concrete. The remaining unsealed specimen in each batch was left unponded and served as the control specimen to measure the baseline chloride content in the mix. Additionally, each batch contained enough material to produce three 4 in. by 8 in. compression cylinders, and to perform air content and slump tests on the fresh concrete. The same mix design was repeated for the 14 concrete mixes required to prepare all the necessary specimens, including those exposed to freeze-thaw cycles. Table 4.3.2 shows the specimens included in a sample chloride ion analysis batch, including the treatment and ponding conditions of each specimen.

The specimens used to test the depth of penetration of the 13 selected deck sealants were cast in one batch. This batch was designed to produce fourteen 3 in. by 4 in. by 16 in. depth of penetration specimens, as well as one 3 in. by 11 in. by 11 in. specimen. Similar to the chloride ion analysis batches, the batch used to test the depth of penetration of the deck sealants contained enough material to produce three 4 in. by 8 in. compression cylinders, and to perform air content and slump tests on the fresh concrete.

Table 4.3.2 Treatment and ponding conditions of specimens in a typical batch

Specimen Number	Treatment Condition	Ponding ?
1	Control	N
2	Untreated	Y
3	Untreated	Y
4	Untreated	Y
5	Treated, Sealer A	Y
6	Treated, Sealer A	Y
7	Treated, Sealer A	Y
8	Treated, Sealer B	Y
9	Treated, Sealer B	Y
10	Treated, Sealer B	Y

4.3.2 Casting and curing procedures

Concrete batches were cast in accordance with ASTM C 192 “Making and Curing Concrete Test Specimens in the Laboratory” (2004) given the equipment available at the WSMTL. Mixes were prepared in a 3.5 cubic ft. automatic concrete mixer. Prior to mixing each test batch, a “butter” batch was prepared and mixed. The “butter” batch, approximately one-third the size of the test batch, was used to coat the mixer and to test the fresh air content, which allowed adjustment of the air entrainment used in the test batch if necessary. Materials were added to the mixer in the following order: coarse aggregate, water, fine aggregate and cement. The concrete was mixed for three minutes before stopping the mixer and covering the concrete for three minutes. Then the concrete was mixed for a final two minutes. The slump and fresh air content of the concrete were tested, and any batch that did not fall within the range of acceptable air content and slump was discarded.

All batches with acceptable air content and slump were cast into the design size and number of specimens for each batch. All specimens were consolidated on a vibrating table for 15 to 20 seconds, or until all large air bubbles had risen to the surface of the specimen. Specimens were given a smooth finish with a steel trowel, then covered with wet burlap and a polyethylene sheet for 24 hours. After 24 hours the specimens were removed from the forms, labeled, and moved to the wet cure room where they remained until 14 days old. The concrete was then removed from the wet cure room and allowed to air cure for an additional 14 days.

4.3.3 Sealant application

At 21 days of age, the specimens intended to be sealed were removed from the curing area and prepared for sealing. The specimens used for the chloride ion analysis were sealed on one 11 in. by 11 in. face, while the depth of penetration specimens were sealed on a 4 in. by 16 in. face. The mass of sealant applied to each specimen was calculated based on the area of the surface to be sealed, and the density and coverage rate of the sealant specified by the manufacturer. If the manufacturer specified one coverage rate, e.g., 150 square feet of coverage per gallon of sealant, that rate was applied. However, if the manufacturer supplied a range of suitable coverage rates, the middle of the range was used. All sealants were applied using a low pressure paint sprayer, set to 25 pounds per square inch of pressure. A removable, reusable wood guard was constructed and positioned over each specimen when applying the sealant to allow material to only hit the target area.

Each specimen was weighed dry and its mass recorded before sealing. After determining the target mass of the specimen with the sealant, some sealant was applied to the specimen and the specimen was reweighed. This process was repeated until the target mass was reached. Table 4.3.3 shows the density and coverage rate for each sealant, and the corresponding target mass of sealant applied for both specimen sizes used in the test program.

Table 4.3.3 Density, coverage rate and target mass of sealant applied for each specimen size

				Target Mass of Sealant Applied (grams):	
	Sealant	**Density** (lb/gal)	**Coverage Rate** (ft^2/gal)	**Chloride Ion Analysis Specimens** (3" x 11" x11")	**Depth of Penetration Specimens** (3" x 4" x 16")
1	TK 290-WB	7.9	150	20.1	10.6
2	Baracade WB 244	8.4	125	25.6	13.5
3	Hydrozo Enviroseal 20	8.16	137.5	22.6	12.0
4	Hydrozo Enviroseal 40	7.9	150	20.1	10.6
5	Aquatrete BSM 20	7.9	150	20.1	10.6
6	TK 290 WDOT	6.72	150	17.1	9.0
7	Sonneborn Penetrating Sealer 40 VOC	6.67	187.5	13.6	7.2
8	Hydrozo Silane 40 VOC	6.67	175	14.5	7.7
9	Eucoguard 100	6.78	125	20.7	10.9
10	Aquanil Plus 40	6.68	125	20.4	10.8
11	V-Seal	9.12	175	19.9	10.5
12	Penseal 244	7.26	187.5	14.8	7.8
13	Powerseal 40%	8.39	187.5	17.1	9.0

4.4 Ponding and Chloride Ion Analysis

In this study, the test methods described in the AASHTO T 259 and T 260 standards were used to determine the resistance provided by the sealants to chloride ion intrusion. The AASHTO T 259 test procedure was used for the preparation and ponding of the specimens, while the AASHTO T 260 method was used for sample extraction and chloride ion analysis.

4.4.1 Surface abrasion and preparation of specimens

Following sealant application at age 21 days, the specimens were returned to the air cure area for another seven days. At 28 days old, samples were transported to the WisDOT Materials Testing Laboratory where sandblasting of the top surface of the specimens was performed in accordance with the requirements of AASHTO T 259. The standard required that the top 3.2 +/- 1.6 mm (1/8 +/- 1/16 inch) of the top surface of each specimen be abraded by grinding or sandblasting, to simulate abrasion that would occur on bridge decks due to vehicular traffic. To ensure that the amount of material removed fell within the limits of AASHTO T 259, a depth measurement device was specially designed for this study and used during sandblasting. The depth measurement device was designed to fit around the specimen as shown in Figure 4.4.1. Before sandblasting, a gauge on the depth measurement device was adjusted so that the tip of a pointed rod rested flush with the top surface of the specimen. With the rod held in place, a second gauge was adjusted which would allow the tip of the pointed rod to again rest flush with the top surface of the specimen after removing the top 3.2 mm (1/8 inch) of material. The depth of sandblasting was verified at a minimum of six random locations on the top surface to ensure the amount of material removed from each area of the block was within the tolerance of AASHTO T 259 (3.2 +/- 1.6 mm).

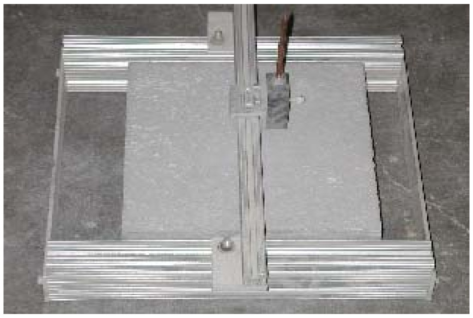


Figure 4.4.1 Sandblasting depth measurement device around specimen

After sandblasting, specimens were returned to the air cure area in the WSMTL, where they remained to further dry for the next two weeks. Just prior to the end of the two weeks of drying, approximately day 41, specimens were removed from the air cure area and prepared for ponding. A commercially available expansion foam was applied around the perimeter of the specimens to create a dam approximately one inch wide by one inch tall. The foam was allowed to cure overnight per manufacturers specifications before ponding began on day 42. Figure 4.4.2 shows a sandblasted specimen with an expansion foam dam ready to begin ponding.

Figure 4.4.2 Sandblasted specimen with expansion foam dam ready to begin ponding

4.4.2 Ponding and Freeze-Thaw Cycle Test Procedure

The specimens were moved to the appropriate location to begin ponding after the expansion foam cured to manufacturers specifications. Specimens either remained at the Wisconsin Structures and Materials Testing Laboratory (WSMTL) to be ponded at ambient conditions, or were transported to a temperature controlled room to begin ponding while undergoing freeze-thaw cycles. The freeze-thaw cycles were conducted at the University of Wisconsin Biotron Facility, where one cycle of freezing at -4°F for four hours alternating with thawing at 86°F for 20 hours was performed each day. Two sets of specimens were prepared for each sealant, one which was subjected to freeze-thaw cycles and one which was not. While the freeze-thaw cycle tests are not a component of the AASHTO T 259 standard, they were included in the project to quantify the deterioration of each sealant due to freeze-thaw cycles.

Ponding began on day 42 and continued for 90 days for a total of 90 freeze-thaw cycles on each specimen. Specimens were ponded with a three-percent sodium chloride and water solution of a constant depth of about one-half of an inch in accordance with AASHTO T 259. One-eighth inch thick sheets of plastic were placed on the top of specimens during ponding to retard evaporation of the solution. At the conclusion of ponding, excess solution was removed and specimens were allowed to dry. Before sampling, the top surface of each specimen was wire brushed until all salt crystal buildup was completely removed.

4.4.3 Sample retrieval

Samples for chloride ion analysis were retrieved in accordance with section four of AASHTO T 260. Using a rotary hammer drill with a depth indicator and a one and one-eighth inch diameter drill bit, an oversized hole was drilled to a depth of one-half of an inch. The drilled hole and surrounding area were then cleaned of all material using a vacuum. The larger bit was replaced with a three-fourths inch diameter drill bit and the depth indicator was reset to allow another one-half of an inch of additional drilling. Approximately nine to ten grams of material from the smaller diameter, deeper hole was retrieved using a sampling spoon and placed in a labeled, clean sample container. Although only three grams of material were necessary to perform a single chloride ion analysis, more material was retrieved to allow up to three samples to be tested from each drilled hole. Holes were drilled and samples were retrieved from three locations on each specimen to determine the range of chloride ion content over each specimen. The approximate locations of the three samples removed from each specimen are shown in Figure 4.4.3

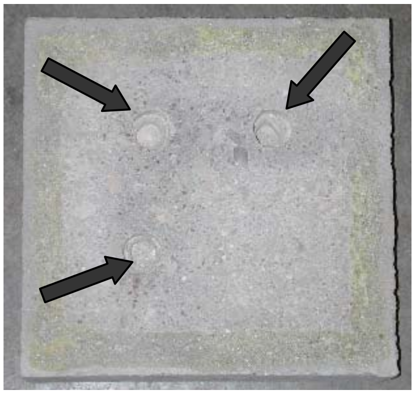


Figure 4.4.3 Location of three samples taken from each specimen for chloride ion analysis

Following retrieval, each sample was passed through a No. 50 sieve. If the sample as collected did not completely pass a No. 50 sieve, additional pulverizing was performed until the entire sample was finer than the No. 50 sieve. All drill bits, spoons, sample containers and other tools were washed with distilled water and rinsed with isopropyl alcohol between samples to prevent contamination.

4.4.4 Equipment and chemicals

The primary equipment used for the chloride ion analysis consisted of a chloride ion selective electrode and a millivoltmeter compatible with the electrode. The electrode recommended in the T 259 standard, a combination chloride electrode, Orion model 96-17, was the electrode used because it did not require the use of a separate reference electrode. Orion model 720 A plus multimeter was used as the millivoltmeter and digital data display.

The procedure to determine the acid-soluble chloride ion content required several chemical reagents and solutions. Concentrated nitric acid (HNO_3) was used in the initial stages of the procedure to decompose the concrete sample. Later in the procedure, methyl orange indicator was used to verify the acidity of the solution. An ionic strength adjuster and chloride activity standard of a known concentration were used to calibrate the electrode and meter each day before use. Two additional solutions, both 0.01 normality concentrations of sodium chloride (NaCl) and silver nitrate ($Ag\ NO_3$), as well as the ionic strength adjuster were used in the titration process.

4.4.5 Sample decomposition

A 3.00-gram sample of pulverized concrete material was transferred from its sample container to a clean 100-mL beaker. Ten milliliters of distilled water were added to the beaker containing the sample, which was swirled to bring the concrete powder into suspension. Next, 3-mL of concentrated nitric acid was added, and swirled continuously until the material was completely decomposed, usually 3-4 minutes. Hot distilled water was stirred into the sample to bring the volume to 50-mL. To ensure that the solution was sufficiently acidic, five drops of methyl orange indicator were added and the color of the solution observed. Additional nitric acid was added to the solution with continuous stirring until a faint pink or red color persisted in the solution. The beaker was covered with a watch glass and heated to boiling on a hot plate over medium heat (250 to 400°C).

After allowing the sample to boil for one minute, it was removed from the hot plate and filtered through a funnel double-lined with filter paper, Whatman No. 41 over No. 40, into a clean 250-mL beaker. The sample residue left in the original sample beaker was washed into the filter setup with hot distilled water. The filter paper was continuously washed with hot distilled water, until the volume of the filtered solution reached 150-mL. The sample was then covered with a watch glass and allowed to cool to room temperature.

4.4.6 Potentiometric Titration

While the sample was cooling, the electrode was filled with the appropriate filling solution and plugged into the millivoltmeter. The electrode was calibrated by verifying that its slope was within the range of chloride concentrations expected in the actual chloride test samples. A standard solution was prepared using the chloride activity standard, ionic strength adjuster and distilled water, and the millivolt reading was measured and recorded. Additional chloride activity standard was then added to the solution to increase the chloride concentration. The millivolt reading and temperature were then measured and recorded. The difference between the millivolt readings from the two solutions, along with the known concentrations of the solutions, defined the slope of the electrode. The electrode was functioning properly when the slope fell within the range specified by the manufacturer. The temperature of the chloride test solution had to match the temperature of the standard solution to ensure accurate millivolt readings during the actual chloride tests. Finally, the calibrated electrode was submerged in a beaker of distilled water to determine the approximate equivalence point of the electrode.

The test sample was prepared for titration when it reached the temperature of the standard solution used to calibrate the electrode. Four milliliters of 0.01 normality sodium chloride solution and three milliliters of the ionic strength adjuster were stirred into the test sample. The electrode was immersed in the test sample solution, and the beaker-electrode assembly was placed beneath the spout of a 25-mL calibrated buret containing 0.01 normality silver nitrate solution. Figure 4.4.4 shows the beaker-electrode-buret assembly during a chloride ion analysis titration. With continuous stirring using a glass stir rod, 0.01 normality silver nitrate solution was added and the volume recorded to bring the millivoltmeter reading to within 40mV below the equivalence point determined in distilled water. Then the 0.01 normality silver nitrate solution was added in 0.20-mL increments with continuous stirring, recording the millivoltmeter reading after each addition.

Figure 4.4.4 Beaker-electrode-buret assembly during a chloride ion analysis titration

As the equivalence point was approached, equal additions of silver nitrate solution caused larger and larger changes in the millivoltmeter reading. Once the equivalence point was reached, the changes in the millivoltmeter reading for equal additions of silver nitrate solution again decreased. The AASHTO T 260 standard requires that the titration continue until the millivoltmeter reading is at least 40 mV past the equivalence point. However, after performing approximately 100 titrations, this requirement was adjusted to continue titrations to approximately 20 mV beyond the equivalence point. Terminating the test 20 mV past the equivalence point allowed for more rapid data collection but did not alter the reliability of the data.

4.4.7 Data Collection

Every addition of silver nitrate solution and the corresponding millivoltmeter reading was recorded by hand and transferred into a computer spreadsheet program. The endpoint of the titration used to calculate the percent chloride ion was determined by plotting the volume of silver nitrate solution added and the millivoltmeter readings. The endpoint of the titration corresponded to the point of inflection of the resultant curve. Figure 4.4.5 shows a typical plot of silver nitrate added versus measured millivolts for a sealed specimen.

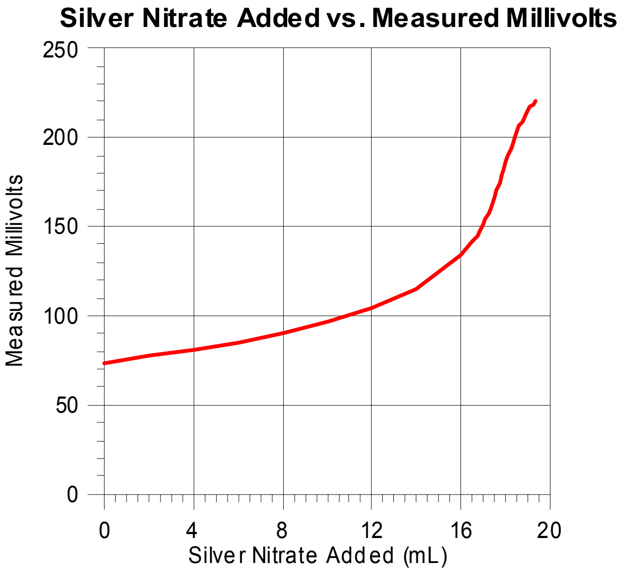


Figure 4.4.5 Typical titration curve for a sealed specimen

The volume of silver nitrate, V_1, added to reach the endpoint of the titration (inflection point) was used to calculate the percent chloride ion in each concrete sample using the following equation taken from the AASHTO T 260 standard:

$$Cl^{-}\,percent = \frac{\left(3.5453\left(V_1N_1 - V_2N_2\right)\right)}{W} \qquad \textbf{(4-1)}$$

where N_1 = normality of the $AgNO_3$ solution
N_2 = normality of the NaCl solution
V_1 = volume added in milliliters of the $AgNO_3$ solution
V_2 = volume added in milliliters of the NaCl solution
W = mass in grams of the original concrete sample.

The percent chloride ion was then converted to pounds of chloride ion per cubic yard of concrete by the following equation:

$$lbs\,Cl^{-}/yd^{3} = Cl^{-}\,percent\left(\frac{UW}{100}\right) \qquad \textbf{(4-2)}$$

where UW is the unit weight of concrete per cubic yard, usually taken as 3915 lb/yd^3 for normal structural mass concrete when the actual unit weight is unknown.

4.5 Depth of Penetration Tests

In this component of the study, a procedure was developed to measure the actual depth of penetration of the deck sealants. These depth of penetration measurements were later compared with the results obtained from the chloride ion analysis tests in an effort to establish a relationship between sealant penetration and performance.

The depth of penetration test used in this program was a modified version of a procedure used by the Oklahoma Department of Transportation to test the depth of penetrating water repellent treatment solutions into Portland cement concrete (OHD L-40, 2003). Concrete specimens sealed on one surface were immersed in a dye-water solution. The dye solution was capable of staining only the untreated concrete, as the area of concrete penetrated by the sealant was left impenetrable to water carrying the dye. The result was a difference in color between sealed and unsealed concrete, which allowed the sealant depth of penetration to be measured. The following sections describe the preparation and test setup, as well as the data collection procedures.

4.5.1 Preparation and test setup

About three months after applying the sealants to the 3 in. by 4 in. by 16 in. specimens, each was saw-cut into four 3 in. by 4 in. by 4 in. sections, to allow multiple depth of penetration measurements to be taken for each sealant. A ¼ in. wide notch was saw-cut into the underside of each of the four sections to within ¾ in. of the sealed surface. The deep notch allowed the specimens to be split apart at the notch, producing a natural crack through the sealed surface. Figure 4.5.1 shows the size and orientation of the depth of penetration specimens, including the location of the saw-cut notch and crack through the sealed surface.

A solution of Sulfonazo III and water was used as the dye solution, prepared by adding small amounts of Sulfonazo III to a pan of water until it became very dark purple in color. The two cracked halves were positioned crack-side down in the pan of dye for 3 – 4 minutes, then rinsed with water and allowed to dry.

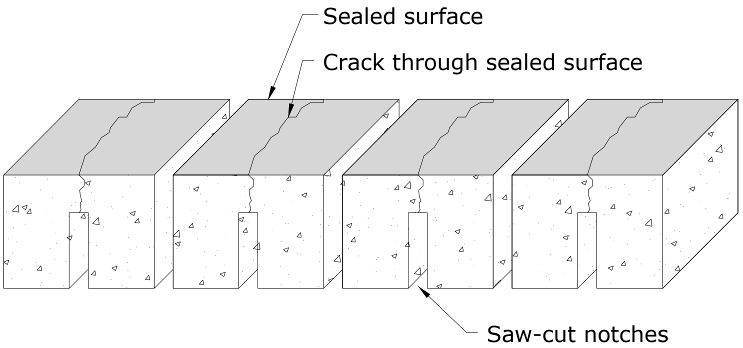


Figure 4.5.1 Depth of penetration specimen cut into four pieces and cracked through sealed surface

4.5.2 Measurement and collection of data

Only the untreated Portland cement concrete was capable of absorbing the water solution carrying the Sulfonazo III dye, and thus became purple in color. The concrete which absorbed sealant was impenetrable to the water carrying the dye, and its color remained unchanged. The boundary between the dyed and undyed concrete was taken as the level of the penetration depth of the sealant. Figure 4.5.2 shows the results of a trial of this test performed on Penseal 244, highlighting the boundary between the dyed and undyed concrete.

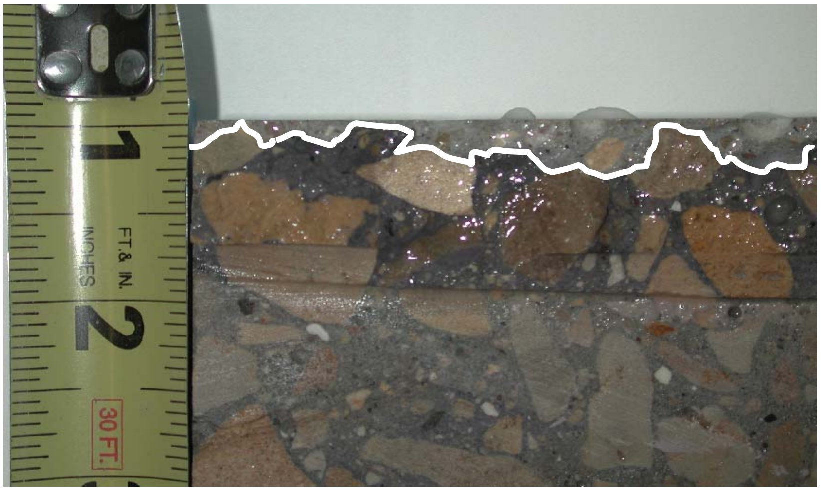


Figure 4.5.2 Depth of penetration profile measured on a trial specimen

Once all specimens were dyed, each piece was rinsed with water, which intensified the color difference between the dyed and undyed concrete and allowed for better measurement of the sealant depth of penetration. Each specimen was divided into four, one inch wide segments. The minimum and maximum depth of penetration within each one inch wide segment was measured to the nearest tenth of a millimeter using a caliper. The minimum and maximum penetration was averaged for each section, and an overall average depth of penetration was computed using all the measurements from a given sealant.

Chapter 5

Test Program – Crack Sealants

5.1 Introduction

In this chapter, the test program used in this study to assess the performance of the crack sealants is presented. Test methods, procedures, specimens and testing equipment used are described in detail.

5.2 Program Description

The primary objective of this task of the study was to assess the effectiveness of the selected sealants to penetrate cracks, to bond to crack walls and to endure crack opening and closing with and without exposure to freeze-thaw cycles. To achieve this goal, concrete specimens with prescribed crack widths were prepared. Cracks were then filled with a sealant that was allowed to cure before testing. Each specimen was saw-cut at the ends through its thickness to measure the depth of penetration of the sealant. To measure the bond strength of the sealants, the specimens were loaded and split through the crack using a test procedure similar to that used for obtaining the splitting tensile strength of cylindrical concrete specimens (see section 2.3.3). To obtain a measure of the deterioration of the bond strength between the sealant and the crack walls, additional specimens were prepared and subjected to 300 freeze-thaw cycles prior to loading. Casting, preparation, and sealing of the concrete specimens, as well as the equipment and test procedures used are described in further detail in the following sections.

5.3 Description of Test Specimens

A single size concrete specimen was used to conduct both the depth of penetration and bond strength tests. The chosen specimen size was 3 in. by 4 in. by 8 in., which was obtained by casting 3 in. by 4 in. by 16 in. units and saw-cutting them in half. This size was chosen because of the desire to create a natural crack through the thickness. In addition, a 3 in. by 4 in. by 8 in. specimen provided sufficient depth for sealants to penetrate, and the bond strength could be accurately measured with the test equipment in the WSMTL. Also, steel forms were available in the WSMTL for casting the specimens, and the standard freeze-thaw cycle test could be adapted to a specimen of that size.

5.3.1 Mix design

The concrete mix design used in the crack sealant test program was identical to the mix design used in the deck sealant test program described in section 4.3.1 of this report.

Each batch was designed to produce twelve 3 in. by 4 in. by 16 in. specimens and three 4 in. by 8 in. compression cylinders. After casting each 16 in. long specimen was cut in half lengthwise to produce 24 bond strength/depth of penetration specimens. Additionally each batch contained enough material to perform air content and slump tests on the fresh concrete. The same mix design was repeated for the 12 concrete mixes required to prepare all required specimens.

5.3.2 Casting and curing procedures

The casting and curing procedures used in the crack sealant test program were identical to the procedures used in the deck sealant test program. All batches with acceptable air content and slump were cast into twelve 3 in. by 4 in. by 16 in. prisms, and three 4 in. by 8 in. compression cylinders. Complete details of the casting and curing procedures used in both the deck sealant and crack sealant test programs are described in section 4.3.2 of this report.

5.3.3 Cracking of specimens

While saw cutting cracks into specimens would allow crack widths to be measured very easily and accurately, the cracks would have an unrealistic smooth surface. To measure the true effectiveness of a crack sealer, it was necessary to create a surface similar to that encountered in real cracks. To create the crack, a 5/8 in. wide by ¼ in. deep notch was saw cut using a masonry saw in the center of each of the two 4 in. by 8 in. faces of the specimens. The notch on the top face of each block was then widened at the ends to 1 ½ in. to allow for accurate measurement of the crack width. A 9/16 in. diameter steel rod was placed in each notch which concentrated the loading to a plane through the center of the specimen as shown

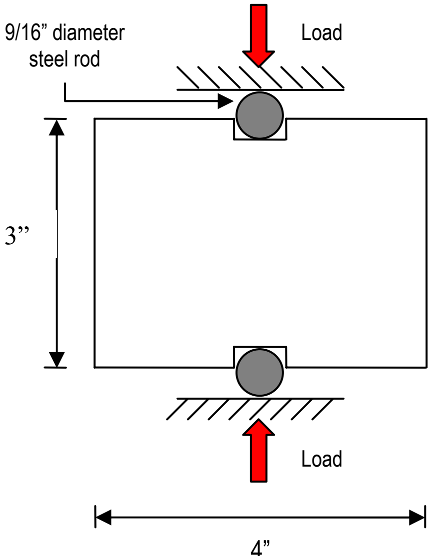


Figure 5.3.1 Setup and test procedure used to crack specimens

in Figure 5.3.1. A one inch thick vee-notched steel plate rested on the top steel rod, which was then loaded manually in the testing machine until cracking of the specimen. After cracking, the specimens were returned to appropriate curing area until they reached 28 days of age. Figure 5.3.2 shows a photograph of the setup used for cracking the specimens.

Figure 5.3.2 Photograph of the setup used for cracking specimens

5.3.4 Formation and measurement of crack widths

Four different crack widths were chosen based on crack width ranges encountered in practice as defined in the current WisDOT Bridge Inspection Pocket Manual. According to this manual, the hairline category included all cracks less than 0.06 in. wide, narrow cracks ranged from 0.06 in. to 0.1 in. wide, medium cracks spanned 0.1 in. to 0.19 in. in width, and the wide category covered any cracks greater than 0.20 in wide. Crack width ranges for each category are shown in Table 5.3.1. In this test program, one crack width was chosen to represent an intermediate value between the range of values given in the pocket manual in each category. A 0.03125 in. (1/32 in.) width crack was selected to represent a hairline crack, 0.0625 in. (1/16 in.) was chosen as narrow, 0.125 in. (1/8 in.) as medium, and 0.20 in. (1/5 in.) represented a wide crack. Not all sealants were recommended to be used in every crack width category. As a result, some sealants were used only for the hairline cracks while others were used for the larger cracks. Table 5.3.2 shows the sealants tested with each crack width.

Table 5.3.1 Crack width categories

Category	Crack Widths Range (in.)
Hairline	< 0.06
Narrow	0.06 - 0.10
Medium	0.10 - 0.19
Wide	> 0.20

At age 28 days, the cracked specimens were removed from the curing area and prepared for sealing. To create a crack with the desired width, folded aluminum foil was placed between the two cracked halves at the ends of the specimen. The four different crack widths were created using varying layers of foil, which was held in place at both ends of the specimen using C-clamps, as shown in Figure 5.3.3. The crack width was measured near the ends of specimen, using a measuring magnifier resting directly on the surface of the crack. Adjustments were made in either the amount of foil used or the clamping pressure until the target crack width was achieved.

Table 5.3.2 Crack sealants tested with each crack width

	Hairline (< 0.06")	**Narrow (0.06" to 0.1")**	**Medium (0.1" to 0.19")**	**Wide (> 0.2")**
	1/32"	1/16"	1/8"	1/5"
1	Degadeck Crack Sealer	Degadeck Crack Sealer	Degadeck Crack Sealer	TK 9000
2	Denedeck Crack Sealer	Denedeck Crack Sealer	Denedeck Crack Sealer	Duraguard 401
3	Sikadur 52	Sikadur 52	Sikadur 52	
4	Sikadur 55 SLV	Sikadur 55 SLV	Sikadur 55 SLV	
5	SikaPronto 19	SikaPronto 19	SikaPronto 19	
6	Dural 335	TK 9000	TK 9000	
7	Duraguard 401	TK 9030	TK 9010	
8		Duraguard 401	Duraguard 401	

After the specimens were clamped to the desired crack width, the ends were sealed with silicone caulk and the underside was sealed with expansion foam to prevent leakage when the crack sealant was applied. In addition, expansion foam was used at the ends of the top surface of the block to create a dam for the sealant when it was poured into the crack. Figure 5.3.3 shows a typical crack sealer specimen ready to be sealed.

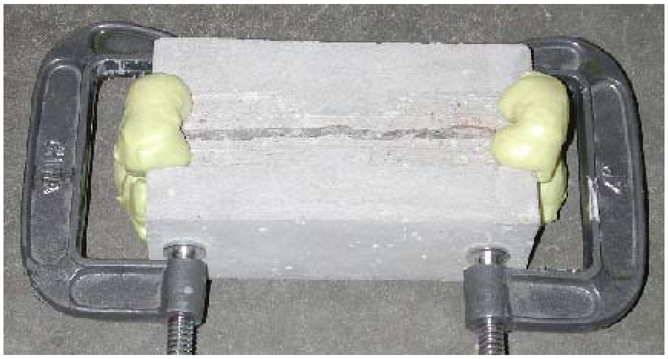


Figure 5.3.3 Typical crack sealer specimen ready to be sealed

5.3.5 Sealant application

The specimens were sealed when the expansion foam and silicone caulk dried to manufacturers' recommendations. Each of the nine crack sealants came in two or three components to be mixed together just prior to application. The products were mixed in the specified proportions, and for the duration given on the technical data sheets from the product manufacturers. After the products were thoroughly mixed, they were poured over and gravity fed into the crack. Working time for the sealants ranged from five to 30 minutes, during which time enough product was applied to completely fill the crack and pool on the top surface of the crack. Set-up time for the products ranged from 15 minutes to over two hours, and drying times ranged from 45 minutes to six hours.

The sealants were allowed to dry overnight before the clamps were removed, and were given at least 14 days to cure until testing. Following the two week curing period, half of the sealed specimens were put in the freeze-thaw chambers, while the other half were prepared for the depth of penetration and bond strength tests. Two inches were saw-cut off the ends of each specimen to measure the depth of penetration of the sealants. The remaining center portion of each specimen was used for the bond strength test, making the bond area approximately 2.5 by 4 inches.

5.4 Depth of Penetration Tests

The depth of penetration of the sealants was measured by visually examining two cross-sections per specimen both with the naked eye and using a measuring magnifier. Figure 5.4.1 shows a cross section of a crack already filled with the sealant. The ability of the sealant to completely or only partially fill the crack was measured and recorded. In addition, if voids were present within the sealant, the shallowest depth at which the first void or air pocket appeared was also recorded. A second void depth was recorded if the void was significantly different in size or shape from the first void.

Figure 5.4.1 Cross section of a specimen filled with a crack sealant

5.5 Bond Strength and Durability Tests

To evaluate and compare the bond strength of the crack sealers, a test procedure similar to ASTM C 496 “Splitting Tensile Strength of Cylindrical Concrete Specimens” was developed. In addition to testing the sealants immediately after the 14 day cure period, companion specimens were sealed and subjected to 300 freeze-thaw cycles before conducting the bond strength test. The latter specimens served to evaluate the bond durability as affected by freeze-thaw cycles. The following sections describe the equipment and test setup, and details of these tests.

5.5.1 Equipment and test setup

In this study, a modified version of ASTM C 496 "Splitting Tensile Strength of Cylindrical Concrete Specimens" was used to measure the bond strength of the concrete specimens used in the crack sealant test program. Typical cylindrical concrete specimens would not fit in the freeze-thaw apparatus at the Wisconsin Structures and Materials Testing Laboratory (WSMTL). The freeze-thaw machine used in this test program would only accommodate prismatic specimens with cross-sections measuring 3 in. by 4 in. and up to 16 in. in length. Since some specimens included in the crack sealant test program had to undergo both freeze-thaw durability tests and bond strength tests, a prismatic specimen was necessary.

Figure 5.5.1 shows the setup of the bond strength test. Specimens were placed in the testing machine in a manner similar to what was used initially to crack the specimens. The specimens were aligned with the sealed surface and saw cut ends both vertical. The surface of the specimen oriented face-up while applying the sealant was also oriented face-up during the bond strength test. Load was applied through a steel rod placed along the top of the specimen, inducing tensile stresses in the bond plane between the two cracked surfaces. Wood bearing strips 1/8 in. thick by ½ in. wide were placed between the concrete specimen and the steel rods to ensure that the load was applied uniformly along the length of the specimen.

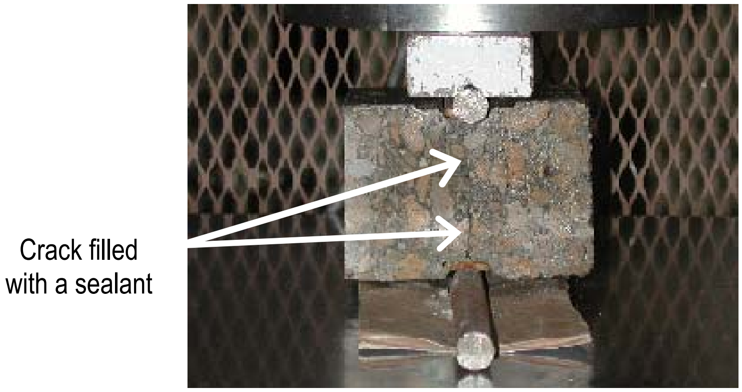


Figure 5.5.1 Setup used to test the bond strength of the crack sealant specimens

The load was applied automatically at a displacement-controlled rate of 0.02 inches per minute. This loading rate is approximately the same rate specified by ASTM C 496 for testing cylindrical specimens. For most specimens, cracks initiated at the bottom and propagated along the sealed surface. A test was terminated automatically when the load dropped by twenty percent or more of the peak load. Test data were collected and stored in electronic spreadsheets, included the displacement, load and characteristics of the failure. The failure could be either a bond failure, a failure in the concrete adjacent to the sealed crack or a failure within the sealant. Combinations of any of the three failure modes could also result. The peak load reached in each test was defined as the bond strength.

5.5.2 Freeze-thaw cycle tests

The relative durability of the sealants was measured by subjecting specimens to 300 freeze-thaw cycles before testing for bond strength. Sealants severely affected by freeze-thaw cycles were expected to lose their ability to remain fully bonded to crack walls or to exhibit a reduced bond strength.

The procedure outlined in ASTM C 666 "Resistance of Concrete to Rapid Freezing and Thawing" was used as a guide when performing the freeze-thaw cycle tests. The specimen size required in ASTM C 666 was between 3 in. and 5 in. in width, depth or diameter, and between 11 in. and 16 in. in length. However, the available containers in the freeze-thaw apparatus at the WSMTL could only accommodate 3 in. by 4 in. by 16 in. specimens. Therefore, a minor deviation from the specimen size specified in ASTM C 666 was necessary. This modification in specimen size, however, was not considered to significantly affect the test results.

Three hundred freeze-thaw cycles were performed in chambers at the WSMTL, where the temperature of the specimens was alternately lowered from 50°F to 0°F and raised from at 0°F to 50°F. While ASTM C 666 requires that 40°F be the maximum temperature during the thawing phase of the cycle, it was increased to 50°F based on concerns over specimens not fully thawing at 40 degrees F during previous studies performed at the WSMTL. Specimens were completely surrounded by water at all times during the cycles, which averaged about 5 hours long. Additionally, ASTM C 666 requires that specimens be removed from the freeze-thaw apparatus at regular intervals during the tests to measure length change and the fundamental transverse frequency. These tests are used to gauge the performance of the concrete due to freeze-thaw cycling, and since the goal of this study was to evaluate sealant performance, these intermediate tests were eliminated. Figure 5.5.2 shows one of the freeze-thaw chambers loaded with specimens at the WSMTL.

Figure 5.5.2 Freeze-thaw chamber at the WSMTL loaded with crack sealant specimens

At the conclusion of the freeze-thaw cycles, specimens were removed from the chambers and allowed to dry. Within the next few days the specimens were prepared and tested for the bond strength as described previously in section 5.5.1.

Chapter 6

Deck Sealants – Test Results and Discussion

6.1 Introduction

In this chapter, results of the tests conducted on the deck sealants are presented and discussed. These results include the data obtained from the chloride ion analysis and depth of penetration tests. Based on the analysis of the test data, the sealants were ranked and assigned to a performance group category.

6.2 Test Results

6.2.1 Measured concrete properties

As described in section 4.3.1, the fresh air content and slump were measured for each batch of concrete. The results of these measurements were used as the criteria to accept or reject a given batch. The values of fresh air content and slump for each batch of concrete used in the deck sealant test program are given in Table 6.2.1. Batches 1 through 14 listed in the table were used to perform the chloride ion analysis, while batch 15 was used to perform the depth of penetration tests on the deck sealants. All of the values for the fresh air content fell within five and seven percent, i.e., within the range of acceptable air contents for the given mix design. Likewise, the results from the slump test ranged from 2.5 inches to 3.75 inches, which also fell within the acceptable range of two to four inches for the given mix design.

In addition, compressive strength tests were conducted at age 28 days on three 4 in. by 8 in. cylinders cast from each batch of concrete. The purpose of the cylinder compressive strength tests was to verify that the concrete used in the test program met the strength requirements of typical Grade D concrete, which has a design compressive strength of 4,000 psi according to the Wisconsin Bridge Manual.

Table 6.2.1 Measured concrete properties for specimens with deck sealants

Batch	Fresh Air Content (%)	Slump (in.)	Compressive Strength Data			
			Cylinder #	Strength (psi)	Batch Average Strength (psi)	
1	6.3	3.0625	1	5910	6113	(205)*
			2	6320		
			3	6110		
2	5.0	2.5	4	6560	6637	(80)
			5	6630		
			6	6720		
3	6.0	2.75	7	6670	6883	(185)
			8	6980		
			9	7000		
4	6.5	3.25	10	6380	6603	(220)
			11	6820		
			12	6610		
5	6.3	3.75	13	6190	6353	(189)
			14	6310		
			15	6560		
6	6.5	3.5	16	6040	6180	(164)
			17	6140		
			18	6360		
7	5.3	3.0	19	6310	6403	(107)
			20	6380		
			21	6520		
8	6.3	2.75	22	6890	6697	(175)
			23	6650		
			24	6550		
9	5.4	2.875	25	6430	6820**	(552)
			26	7210		
			27	3310		
10	5.7	3.25	28	6270	6237	(491)
			29	5730		
			30	6710		
11	5.0	2.5	31	7210	7047	(249)
			32	6760		
			33	7170		
12	5.7	3.0	34	6940	6817	(258)
			35	6520		
			36	6990		
13	6.3	3.0	37	6040	6157	(115)
			38	6270		
			39	6160		
14	5.7	2.5	40	6620	6683	(203)
			41	6910		
			42	6520		
15	7.0	2.625	43	5110	5580	(432)
			44	5960		
			45	5670		

* Values in parentheses show the standard deviation of the results

** Batch nine average compressive strength and standard deviation based on cylinders 25 and 26 only

The results from all of the compressive strength tests are shown in Table 6.2.1. The last column in Table 6.2.1 gives the batch average strength and standard deviation. The overall average strength for all batches cast in the deck sealant test program was 6,403 psi with a standard deviation of 637 psi. Figure 6.2.1 provides a plot of the compressive strength for each cylinder, and Figure 6.2.2 shows a plot of the batch average compressive strength for all deck sealant concrete. It is clear from both figures that the results were very consistent, with only one obvious outlier in batch nine with a compressive strength of 3,310 psi. All other cylinders easily exceeded the design compressive strength of 4,000 psi.

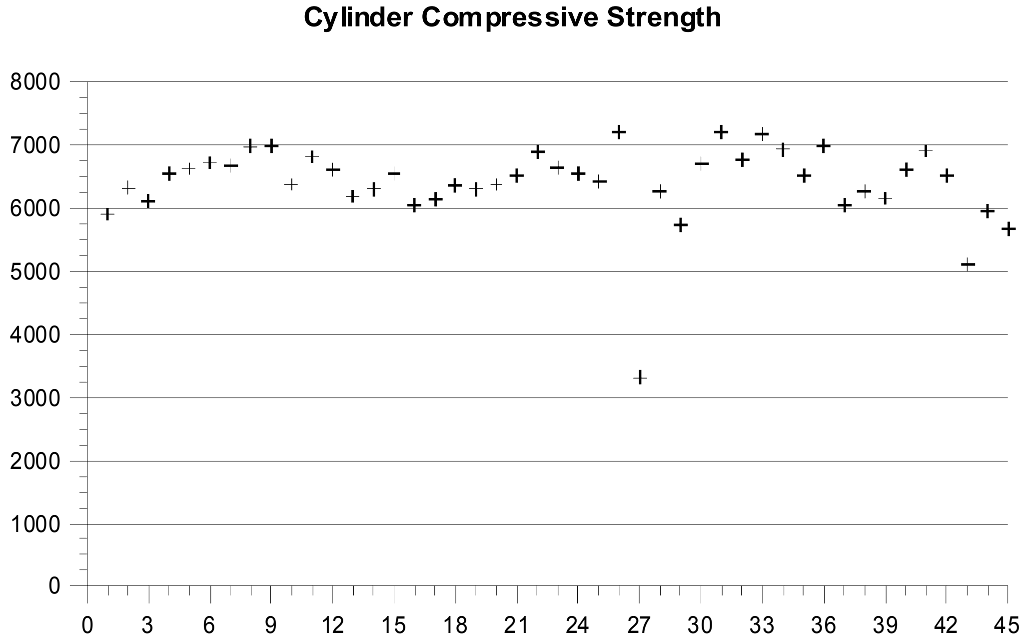


Figure 6.2.1 Cylinder compressive strength of the concrete used in specimens with deck sealants

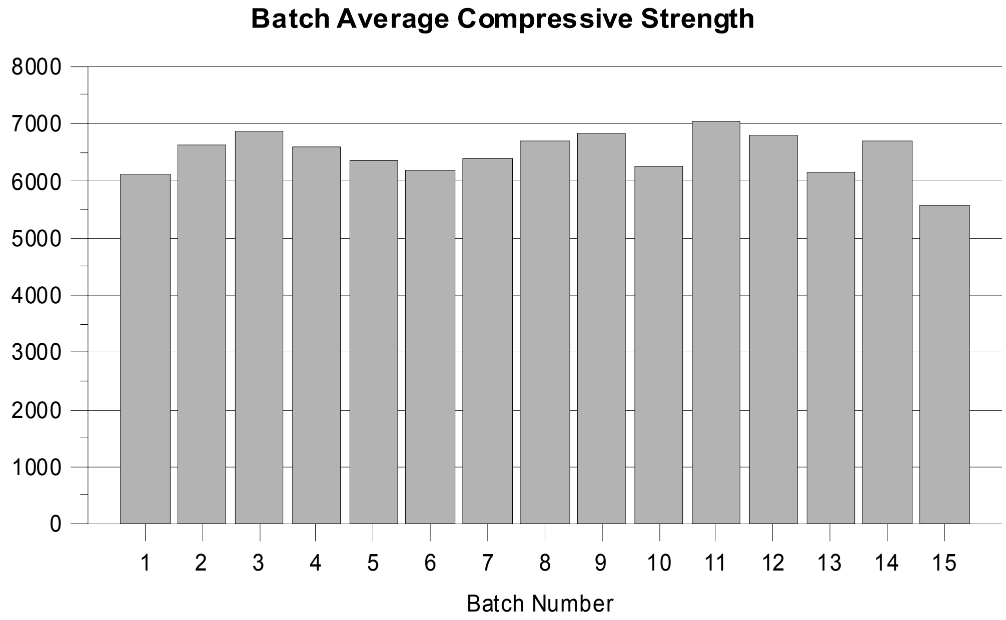


Figure 6.2.2 Batch average compressive strength of the concrete used in specimens with deck sealants

6.2.2 Chloride ion analysis

6.2.2.1 Titration curves

Figure 6.2.3 shows typical titration curves – plots of silver nitrate added versus measured millivolts – for samples taken from one sealed concrete specimen. (All titration curves shown in the following sections were cropped to display only the area of interest around the point of inflection). The data presented in Fig. 6.2.3 shows virtually no scatter among samples taken from the same hole as observed by nearly overlapping curves on each plot. This result was typical to all samples and attests to the excellent reliability of the procedure to determine the chloride content using multiple samples from the same hole.

Figure 6.2.4 (a) displays the same data shown in Figure 6.2.3, but all plotted on the same graph, while Figure 6.2.4(b) and (c) display the similar data obtained from two other specimens, sealed with a different sealant. It can be seen that titration curves can show considerable scatter depending on the location where the samples were extracted from the specimen. In other words, the chloride content can vary significantly within a given specimen.

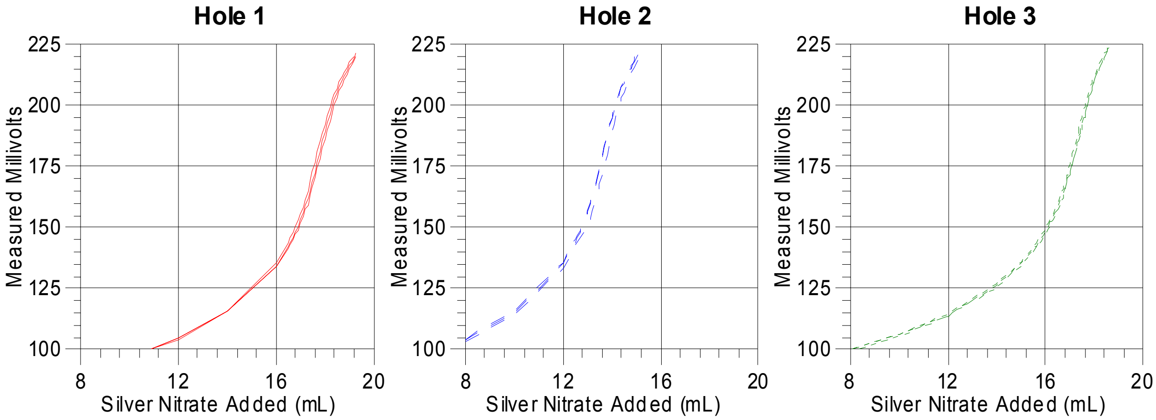
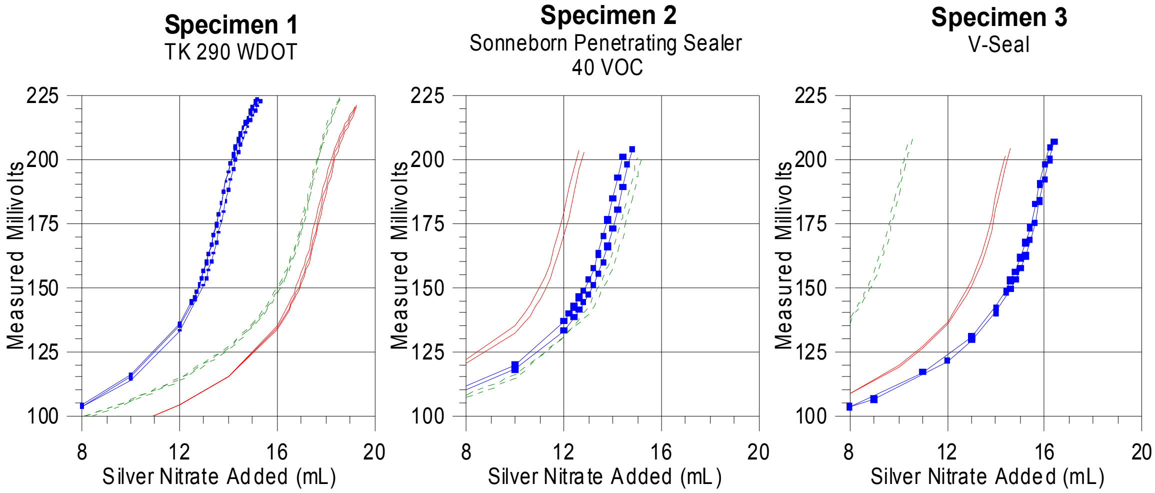


Figure 6.2.3 Titration curves for samples taken from three holes drilled in one sealed specimen.

The observed scatter in the chloride content at different locations in the same specimen may be attributed to several factors. For example, although every effort was made to apply sealant uniformly over the top surface of each specimen, some areas of the specimen may have been provided with more sealant than others. Also, and most likely the main reason, the depth of penetration of a sealant can vary substantially over the surface (this will be discussed in greater detail in subsequent sections of this report). Therefore, the depth of protected concrete, which is resistant to chloride ion intrusion, will vary considerably over a surface. These two factors, combined with even minor variations in the depth of sandblasting could result in a layer of sealant of varying thickness.



(a) (b) (c)

Figure 6.2.4 Titration curves for samples taken from three specimens treated with different sealants.

In Figure 6.2.5, the titration curves obtained from all three specimens sealed with the same sealant are shown. It can be seen that samples taken from different specimens show no more scatter than that observed from samples taken from the same specimen (see Figure 6.2.4).

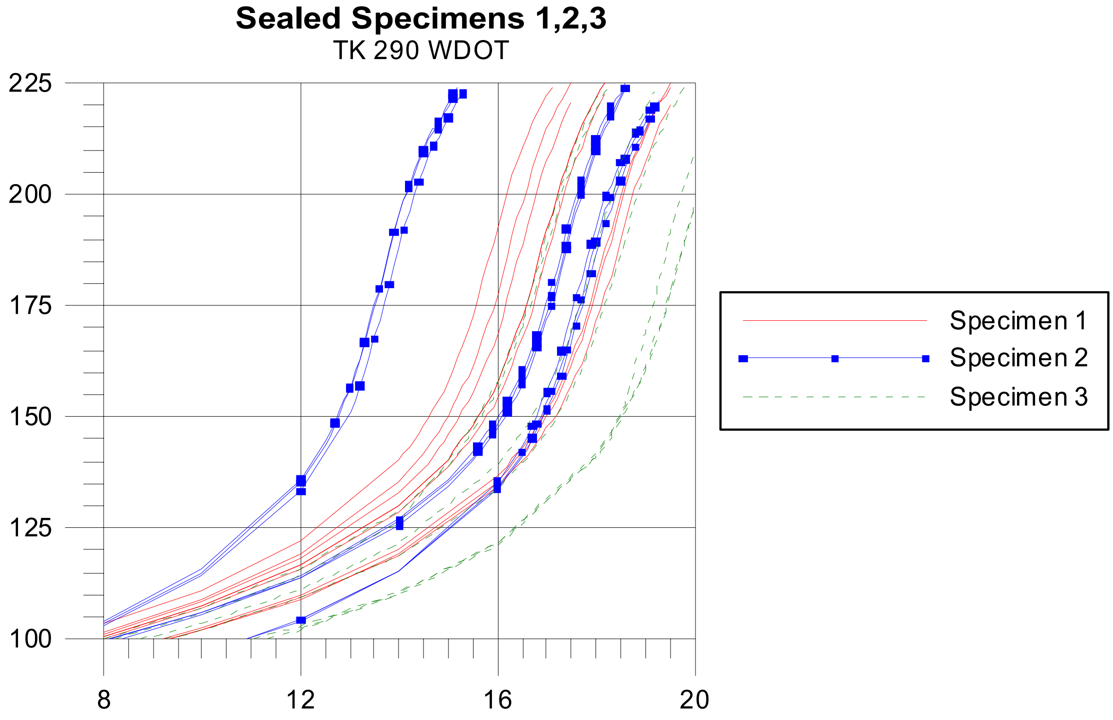


Figure 6.2.5 Chloride ion analysis results for samples taken from three specimens treated with the same sealant.

Since the results from samples tested from the same hole exhibited virtually no scatter (see Figure 6.2.3), and nearly all the scatter in the measurements could be attributed to samples taken from different holes or from different specimens, the number of samples tested from each hole was reduced from three to two samples in order to expedite the data collection. Enough material was still retrieved from each hole to allow a third sample to be tested if results from the first two samples conflicted. A third sample was tested only if the results from the first two samples differed by more than 0.0068 percent chloride. This value was chosen because it corresponds to the difference of chloride content allowed for two properly conducted tests by the same operator on the same material as given in the precision statement in the AASHTO T 260 standard. It should be mentioned, however, that this criterion was always met and thus only two samples were needed in the rest of the study.

6.2.2.2 Determination of the equivalence point and chloride ion content

Once a titration curve was produced for each sample, a horizontal line was drawn from the vertical axis, intersecting the curve at the point of inflection. The point of inflection was established by adding equal additions of silver nitrate and recording the corresponding millivoltmeter readings. The volume of silver nitrate which caused the largest increase in millivoltmeter reading corresponded to the point of inflection of the curve. A vertical line was then drawn connecting the point of inflection of the curve with the horizontal axis of the graph. The point where this line intersects the horizontal axis corresponds to the endpoint of the titration. This procedure is illustrated in Figure 6.2.6 for one sample, with the dashed line intersecting the curve at the point of inflection, and the arrow indicating the volume of silver nitrate needed to reach the endpoint of the titration.

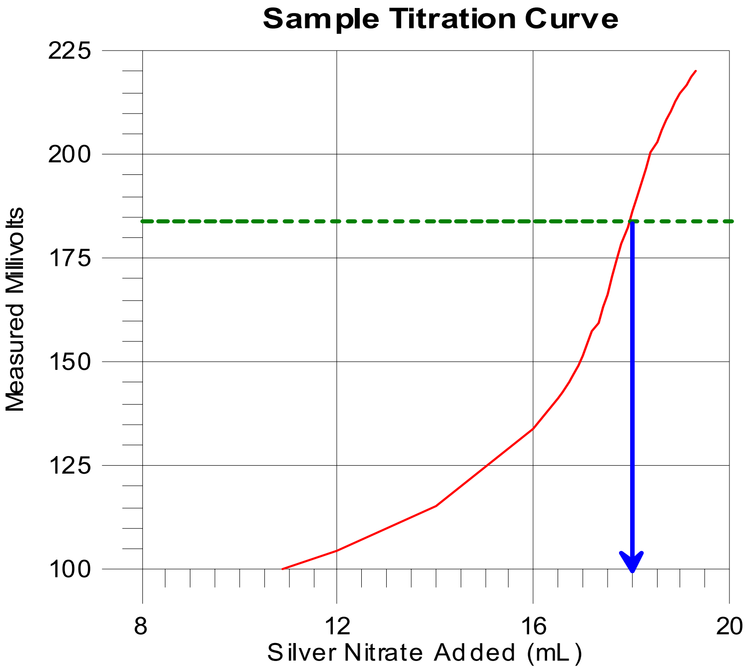


Figure 6.2.6 Sample titration curve showing the point of inflection and the corresponding endpoint of the titration.

The volume of silver nitrate needed to reach the endpoint of the titration, V_1, was used to calculate the percent chloride ion in the sample, which was then converted to pounds of chloride ion per cubic yard of concrete. The procedure and equations used to calculate the percent chloride ion and pounds of chloride per cubic yard of concrete were described in section 4.4.7. These equations are repeated below:

$$Cl^{-}\,percent = \frac{\left(3.5453\left(V_1N_1 - V_2N_2\right)\right)}{W} \qquad \textbf{(4-1)}$$

$$lbs\,Cl^{-}/yd^{3} = Cl^{-}\,percent\left(\frac{UW}{100}\right) \qquad \textbf{(4-2)}$$

All variables were previously defined in section 4.4.7.

The percent chloride ion and pounds of chloride per cubic yard of concrete were calculated for each sample, and the average chloride ion content was calculated for each treatment condition for a given batch. The average baseline chloride ion content calculated from the control specimen (specimen not subjected to ponding) in each batch was subtracted from the average values of sealed and unsealed specimens in the same batch to compute the average absorbed chloride ion content. An example of the obtained results are tabulated in Table 6.2.2 for batch number six. The last column in Table 6.2.2 displays the average absorbed chloride ion content for sealed and unsealed specimens. A summary of the results for all other batches is given in Appendix B.

a) Performance of sealants not subjected to freeze-thaw cycles

Table 6.2.3 shows the average absorbed chloride content obtained for all deck sealants not exposed to freeze-thaw cycles. Column [1] in Table 6.2.3 shows the average absorbed chloride for the sealed specimens, while column [2] shows the average absorbed chloride for the unsealed specimens from the corresponding batch. The calculated standard deviation is shown in parentheses for the sealed and unsealed specimens in each column.

Table 6.2.2 Average absorbed chloride ion content in specimens from batch number six

Treatment Condition	Average/hole (lb Cl^-/yd^3)	Average/specimen (lb Cl^-/yd^3)	Overall Average (lb Cl^-/yd^3)	Average absorbed chloride (lb Cl^-/yd^3)
Unsealed (Control)	1.22	1.21	1.21 (0.08)*	N/A
	1.30			
	1.12			
Unsealed	5.53	6.14	6.98 (1.27)	5.77
	7.20			
	5.68			
	6.09	7.05		
	5.98			
	9.08			
	8.90	7.76		
	7.45			
	6.93			
Aqua-Trete BSM 20	6.62	5.56	6.07 (1.32)	4.86
	3.09			
	6.96			
	6.30	6.62		
	6.61			
	6.95			
	5.13	6.03		
	5.45			
	7.52			
TK 290-WDOT	6.05	6.17	6.15 (0.75)	4.93
	6.81			
	5.66			
	6.47	5.75		
	4.57			
	6.20			
	7.27	6.52		
	6.42			
	5.87			

* Values in parentheses show the standard deviation of the results

The last column in Table 6.2.3 shows the ratio between the measured chloride content for the sealed specimens and that of the unsealed specimens, and the corresponding standard deviation of the ratio. The standard deviation of the chloride content ratio was estimated as the square root of its variance using the following equation (Mood et al., 1974):

$$\operatorname{var}\left[\frac{X}{Y}\right] \approx \left(\frac{\mu_x}{\mu_y}\right)^2 \left(\frac{\operatorname{var}[X]}{\mu_X^2} + \frac{\operatorname{var}[Y]}{\mu_Y^2} - \frac{2\operatorname{cov}[X,Y]}{\mu_X \mu_Y}\right) \qquad \textbf{(6-1)}$$

where:

$\mathrm{var}\left[\frac{X}{Y}\right]$ = variance of the ratio of absorbed chloride

$\mathrm{var}[X]$ = variance of the chloride content of the sealed specimens

$\mathrm{var}[Y]$ = variance of the chloride content of the unsealed specimens

μ_X = average absorbed chloride of the sealed specimens

μ_Y = average absorbed chloride of the unsealed specimens

$\mathrm{cov}[X,Y]$ = covariance of the results from sealed and unsealed specimens

The chloride ion analysis results from the sealed and unsealed specimens were assumed to be independent, thus the covariance of the results from the sealed and unsealed specimens ($\mathrm{cov}[X,Y]$) was taken as zero.

Table 6.2.3 Average chloride content absorbed in specimens not subjected to freeze-thaw cycles

Sealant	Concrete Batch	Absorbed Chloride -- ***Sealed*** Specimens (lb Cl^-/yd^3) [1]		Absorbed Chloride -- ***Unsealed*** Specimens (lb Cl^-/yd^3) [2]		***Sealed/Unsealed*** [1]/[2]	
Solvent-based:							
Aquanil Plus 40	9	1.41	(0.71)*	2.81	(1.01)	0.50	(0.31)
Eucoguard 100	9	3.55	(1.77)	2.81	(1.01)	1.27	(0.78)
Hydrozo Silane 40 VOC	8	1.59	(1.00)	4.24	(0.71)	0.37	(0.24)
Penseal 244	10	2.22	(2.18)	3.93	(0.76)	0.57	(0.56)
Sonneborn Penetrating Sealer 40 VOC	8	1.96	(1.17)	4.24	(0.71)	0.46	(0.29)
TK 290-WDOT	6	4.93	(0.75)	5.77	(1.27)	0.86	(0.23)
Water-based:							
Aqua-Trete BSM 20	6	4.86	(1.32)	5.77	(1.27)	0.84	(0.29)
Baracade WB 244	5	5.66	(1.11)	5.09	(0.73)	1.11	(0.27)
Hydrozo Enviroseal 20	7	4.83	(1.26)	4.61	(1.26)	1.05	(0.39)
Hydrozo Enviroseal 40	7	4.06	(2.17)	4.61	(1.26)	0.88	(0.53)
Powerseal 40%	11	3.26	(0.88)	4.26	(1.00)	0.77	(0.27)
TK 290-WB	5	5.64	(1.38)	5.09	(0.73)	1.11	(0.31)
V-Seal	10	3.04	(0.96)	3.93	(0.76)	0.77	(0.29)

* Values in parentheses show the standard deviation of results

In Table 6.2.3, a smaller value of the chloride content ratio (last column of the table) represents a better the ability of the sealant to deter chloride ion penetration into the concrete. A large value, i.e., close to 1.0, indicates that the sealant provided little or no protection against the ingress of chloride ions.

The data presented in Table 6.2.3 show four sealants with chloride ratios greater than 1.0 (Eucoguard 100, Baracade WB 244, Hydrozo Enviroseal 20, and TK 290-WB), which may appear contradictory at first glance (i.e., sealed specimens absorbed more chloride than those unsealed). However, it is important to note that the standard deviations are quite large, ranging from 15 to 98 percent of the average absorbed chloride for sealed specimens. The reason for the large standard deviation is attributed to the large variation in the depth of penetration of a sealant, as will be discussed in subsequent sections of this report. It should also be noted that the observed magnitude of the standard deviations as a percentage of the averages is not uncommon for this type of study. Results of a similar study performed at the University of Oklahoma using the AASHTO T 259/260 test method showed standard deviations similar to or even larger than the mean (Bush, 1998).

In general, the results in Table 6.2.3 indicate that Hydrozo Silane 40 VOC was the most effective product at deterring the ingress of chloride ions with a chloride ratio of 0.37, while Eucoguard 100 was the least effective, providing no protection compared to unsealed concrete, with a chloride ratio of 1.27.

In Figure 6.2.7, the average ratio of absorbed chloride is plotted in order of increasing value for all sealants. Sealants that offer the best protection are on the left (lowest absorbed chloride) and those offering the least protection on the right. Vertical lines within each bar represent the mean plus or minus the standard deviation of the computed ratio. Figure 6.2.7 shows that the four sealants with ratios of absorbed chloride greater than one (Eucoguard 100, Baracade WB 244, Hydrozo Enviroseal 20, and TK 290-WB) all have mean minus one standard deviations that extend below a chloride content ratio of one. This shows that even the poorest performing sealants were able to provide some level of protection to the concrete in some areas of the specimen, even though on average these sealants offered virtually no protection. It may also be seen that solvent-based sealants tended to provide better protection to concrete than water-based products. Two exceptions are TK 290-WDOT which is a solvent-based product that performed in the middle range of products, and Eucoguard 100 which performed the poorest of all the sealants.

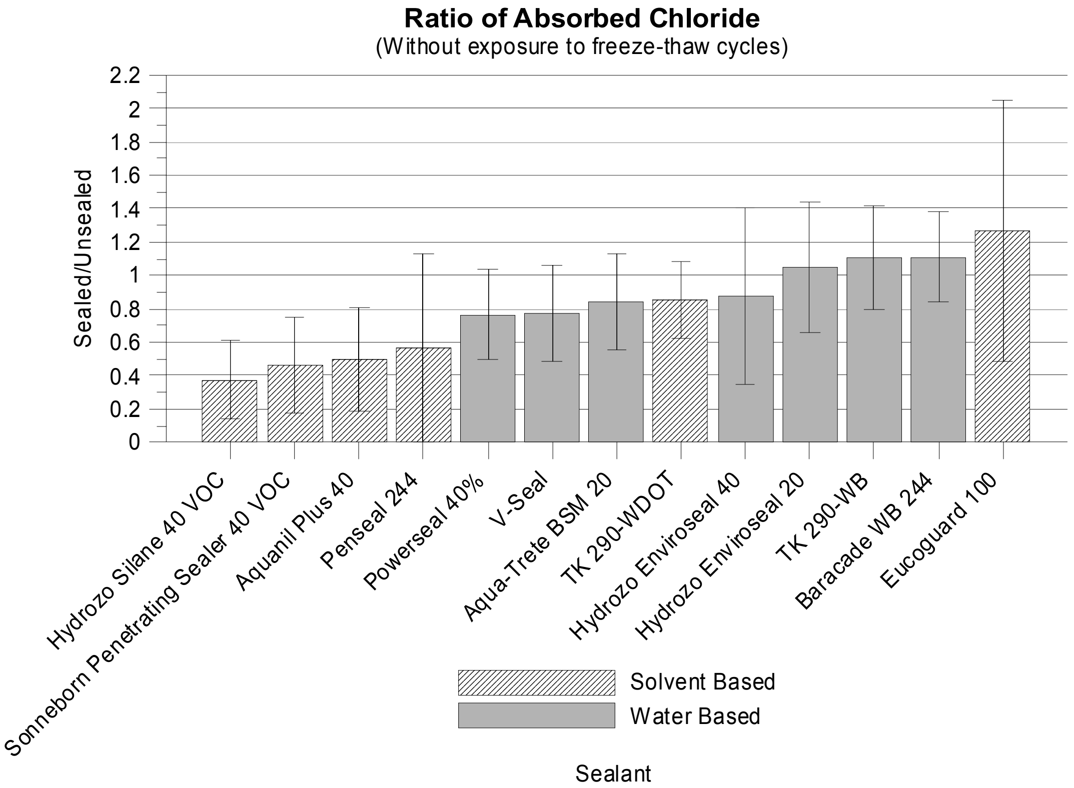


Figure 6.2.7 Ratio of absorbed chloride in specimens without exposure to freeze-thaw cycles

b) Performance of sealants subjected to freeze-thaw cycles

In Table 6.2.4, the average absorbed chloride ion content for two sealants (Aqua-Trete BSM 20 and Hydrozo Enviroseal 40) is compared for specimens with and without exposure to freeze-thaw cycles. Columns [1] and [2] list the absorbed chloride for sealed and unsealed specimens not subjected to freeze-thaw cycles, while columns [3] and [4] show the absorbed chloride for sealed and unsealed specimens subjected to freeze-thaw cycles. The last two columns in Table 6.2.4 show the ratios of absorbed chloride for specimens not subjected to freeze-thaw cycles, as well as those for specimens subjected to freeze-thaw cycles.

The data in Table 6.2.4 show, for example, that the performance of Aqua-Trete BSM 20 was severely affected by the exposure to freeze-thaw cycles. The absorbed chloride for the sealed specimens increased from 4.86 lb Cl^-/yd^3 to 6.99 lb Cl^-/yd^3 resulting in an increase in the ratio of absorbed chloride from 0.84 to 0.99 when the specimens were subjected to freeze-thaw cycles.

Table 6.2.4 Average absorbed chloride content for specimens sealed with Aqua-Trete BSM 20 and Hydrozo Enviroseal 40 subjected to freeze thaw cycles

Sealant	***Non F-T*** Absorbed Chloride -- ***Sealed*** Specimens (lb Cl$^-$/yd^3) [1]	***Non F-T*** Absorbed Chloride -- ***Unsealed*** Specimens (lb Cl$^-$/yd^3) [2]	***F-T*** Absorbed Chloride -- ***Sealed*** Specimens (lb Cl$^-$/yd^3) [3]	***F-T*** Absorbed Chloride -- ***Unsealed*** Specimens (lb Cl$^-$/yd^3) [4]	***Non F-T*** Sealed/Unsealed [1]/[2]	***F-T*** Sealed/Unsealed [3]/[4]
Aqua-Trete BSM 20	4.86 (1.32)*	5.77 (1.27)	6.99 (1.39)	7.08 (1.21)	0.84	0.99
Hydrozo Enviroseal 40	4.06 (2.17)	4.61 (1.26)	4.76 (1.38)	6.31 (2.17)	0.88	0.75

* Values in parentheses show the standard deviation of the results

The performance of Hydrozo Enviroseal 40 was also affected when exposed to freeze-thaw cycles. The absorbed chloride for the sealed specimens increased from 4.06 lb Cl$^-$/yd^3 to 4.76 lb Cl$^-$/yd^3 when exposed to freeze-thaw cycles. The ratio of absorbed chloride was, however, calculated to decrease from 0.88 to 0.75 when exposed to freeze-thaw cycles. This last result would imply that the sealant performed better under exposure to freeze-thaw cycles, and would contradict the conclusion inferred from the increase in the total amount of absorbed chloride. This, however, is not true. The reason for the reduction in the value of the calculated ratio is that the unsealed specimens absorbed significantly more chloride under freeze-thaw cycles (see columns [2] and [4] of Table 6.2.4). In other words, the sealant was very effective at protecting the concrete relative to the unsealed specimens, but its performance did deteriorate somewhat under exposure to freeze-thaw cycles.

As one objective of this study was to determine the degradation of the sealants when exposed to freeze-thaw cycles, the ratio of absorbed chloride as computed above did not provide a good indicator of their performance. Thus, a different quantity was used to compare the sealants' performance under exposure to freeze-thaw cycles. For this purpose, the chloride content of the sealed specimens exposed to freeze-thaw cycles was compared to that of the unsealed specimens without exposure. This approach required that differences in the chloride content of the mix itself among different batches (minimal in most cases–see data for unsealed specimens in Appendix B) be considered in the calculations. The procedure used to account for these differences is presented in Appendix C.

In Table 6.2.5, the absorbed chloride content of the *sealed specimens exposed to freeze-thaw cycles* and that of the *unsealed specimens not exposed to freeze-thaw cycles* are shown. Also shown in the table is the value of the ratio between these two quantities. This ratio is also plotted in Figure 6.2.8 in order of increasing value (i.e., the most effective sealants are located on the left, while the least effective are on the right). The mean plus or minus the standard deviation of the ratio is indicated by a vertical line in each bar.

Table 6.2.5 Average chloride content ratio absorbed in sealed specimens exposed to freeze-thaw cycles.

Sealant	Concrete Batch	Absorbed Chloride -- *Sealed* specimens (lb Cl^-/yd^3) [1]	Absorbed Chloride -- *Unsealed* Specimens (lb Cl^-/yd^3) [2]	***Sealed/Unsealed*** [1]/[2]
Solvent-based:				
Aquanil Plus 40	12	4.70 (1.73)*	3.17 (1.01)*	1.49 (0.72) **
Eucoguard 100	12	4.54 (1.35)	3.17 (1.01)	1.44 (0.62)
Hydrozo Silane 40 VOC	4	2.71 (1.06)	3.60 (0.71)	0.75 (0.33)
Penseal 244	13	3.84 (2.14)	4.54 (0.76)	0.85 (0.49)
Sonneborn Penetrating Sealer 40 VOC	4	1.51 (0.75)	3.60 (0.71)	0.42 (0.22)
TK 290-WDOT	3	5.65 (1.09)	5.45 (1.27)	1.04 (0.31)
Water-based:				
Aqua-Trete BSM 20	3	6.99 (1.39)	5.45 (1.27)	1.28 (0.39)
Baracade WB 244	1	6.52 (1.27)	4.98 (0.73)	1.31 (0.32)
Hydrozo Enviroseal 20	2	4.58 (1.15)	4.40 (1.26)	1.04 (0.40)
Hydrozo Enviroseal 40	2	4.76 (1.38)	4.40 (1.26)	1.08 (0.44)
Powerseal 40%	14	2.77 (0.43)	3.76 (1.00)	0.74 (0.23)
TK 290-WB	1	6.26 (1.49)	4.98 (0.73)	1.26 (0.35)
V-Seal	13	3.56 (1.63)	4.54 (0.76)	0.78 (0.38)

* Values in parentheses show the standard deviation of the results

** Standard deviation estimated using equation 6-1

The data in Table 6.2.5 and Fig. 6.2.8 show that, unlike the results for specimens not exposed to freeze-thaw cycles, there is no clear performance trend between solvent-based and water-based products when exposed to freeze-thaw cycles. Under exposure to freeze-thaw cycles, the sealant which provided the highest level of protection was Sonneborn Penetrating Sealer 40 VOC with a ratio of 0.42, while the sealant with the poorest performance was Aquanil Plus 40 with a ratio of 1.49. It may also be noted that Hydrozo Silane 40 VOC, the sealant that offered the best protection without exposure to freeze-thaw cycles, was still able to effectively deter chloride ion intrusion, though its performance was not as good. Eucoguard 100, was virtually ineffective as was expected based on the results obtained under no exposure to freeze-thaw cycles.

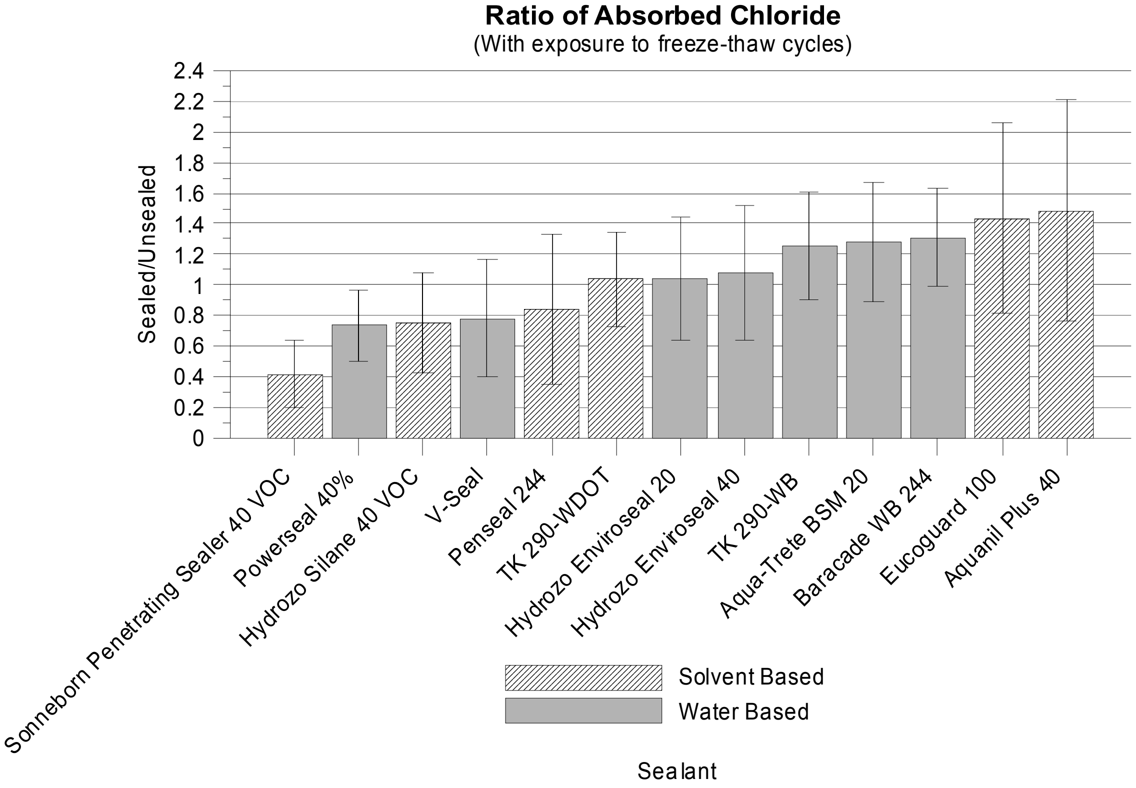


Figure 6.2.8 Ratio of absorbed chloride in specimens exposed to freeze-thaw cycles

6.2.3 Depth of penetration tests

As described earlier in section 4.5.1, each 3 in. by 4 in. by 16 in. depth of penetration specimen was treated with a single sealant and saw-cut into four sections. Each section of a specimen was cracked and placed in a dye-water solution, then used to measure the depth of penetration as described in section 4.5.2. Initially, all of the depth of penetration measurements were taken approximately three days after the sealants were applied. After analysis of the data, however, it was concluded that the initial measurements may have been taken prematurely, not allowing the sealants enough time to penetrate the concrete. Therefore, additional depth of penetration measurements were taken approximately three months after the sealants were applied, which allowed the sealants ample time to penetrate the concrete. The data from the latter measurements is included in this report.

Figure 6.2.9 shows a typical profile of the measured depth of penetration for a specimen sealed with Penseal 244. It is apparent from Figure 6.2.9 that the depth of penetration of the sealant varies considerably over the width of the specimen, ranging from less than 1/16 in. in some locations to greater than 1/4 in. other areas. The amount of variation seen in Figure 6.2.9 was typical of most sealants, and areas of very little penetration were observed in the profile of several sealants.

To obtain a measurement of the penetration depth of a sealant, the exposed surface was divided into four one inch long segments (see Figure 6.2.10). The maximum and minimum depths within each one inch segment were measured using a digital readout caliper for a total of eight measurements per section. Similar measurements were taken for the three other sections treated with the same sealant, for a total of 32 measurements per sealant.

Figure 6.2.9 Sample depth of penetration profile for Penseal 244.

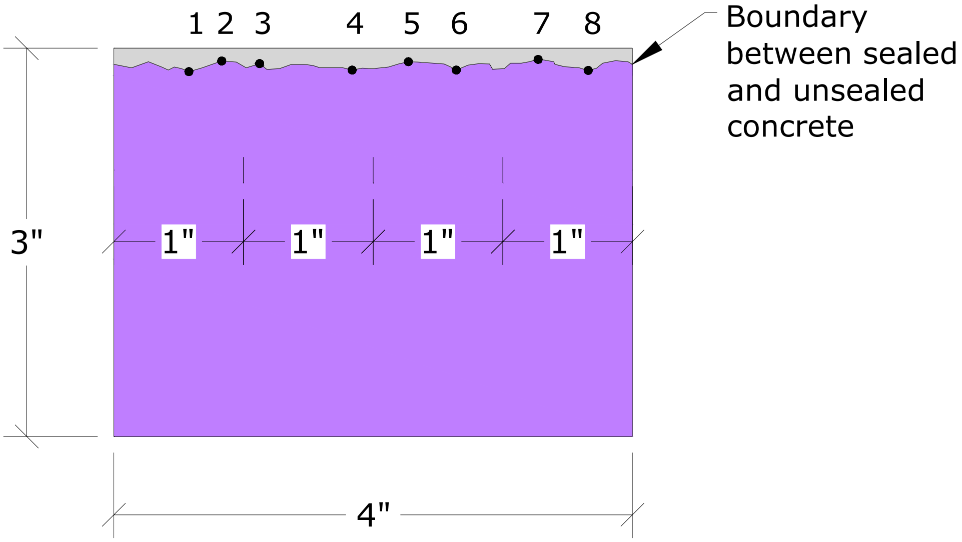


Figure 6.2.10 Measurement of depth of penetration profile in sealed specimens.

The measured depth of penetration for all sealants is shown in Table 6.2.6. The average depth of penetration and corresponding standard deviation of all 32 measurements taken for each sealant are shown in the last column of the table. It is evident from Tables 6.2.6 that the scatter of the measured depth of penetration among the different sections of the same specimen can be quite large. For example, the penetration depth of TK290-WDOT varied from 0.3 mm. to 4.4 mm. within the fourth inch of width of section 3. The standard deviation of all depth of penetration measurements for TK 290-WDOT was 1.5 mm, which is 83% of the average depth of penetration. However, the variability within the measurements Hydrozo Enviroseal 40 was noticeably smaller. The standard deviation of Hydrozo Enviroseal 40 was only 1.0 mm, which is about 48% of the average depth of penetration, and is one-half of the standard deviation of TK 290-WDOT.

Table 6.2.6 Depth of penetration measurements, averages and standard deviations

Sealant	Section	1st inch		2nd inch		3rd inch		4th inch		Overall Average (mm)
		Min (mm)	Max (mm)	Min (mm)	Max (mm)	Min (mm)	Max (mm)	Min (mm)	Max (mm)	
Aquanil Plus 40	1	0.9	2.9	1.6	3.0	1.6	4.7	1.1	3.2	2.5 (1.6)*
	2	1.3	4.1	1.3	5.7	1.5	6.7	1.2	2.9	
	3	1.4	5.0	1.4	5.3	1.3	3.1	0.8	3.1	
	4	0.7	2.0	1.3	2.1	1.2	2.9	2.2	3.2	
Eucoguard 100	1	0.9	2.5	1.1	3.3	0.7	4.5	1.0	1.9	1.8 (1.1)
	2	1.1	3.1	0.9	1.9	1.2	2.6	1.2	1.7	
	3	1.1	3.1	0.9	2.7	1.6	4.6	0.9	1.8	
	4	1.0	2.3	0.6	1.9	1.2	2.4	0.7	1.7	
Hydrozo Silane 40 VOC	1	3.3	6.0	1.5	6.7	5.5	7.1	2.6	4.9	3.8 (2.0)
	2	1.2	3.9	3.0	5.0	3.6	6.4	2.5	5.5	
	3	1.8	5.8	1.2	6.3	1.9	4.2	2.0	4.2	
	4	1.4	3.8	1.2	7.8	1.6	2.8	1.7	4.6	
Penseal 244	1	1.6	2.6	1.8	3.3	2.2	6.9	1.9	4.9	2.7 (1.5)
	2	1.1	6.6	1.9	3.6	1.7	3.4	0.9	3.0	
	3	1.0	2.2	1.7	4.5	1.4	4.6	1.9	2.7	
	4	1.7	2.7	2.4	3.7	1.5	3.5	1.8	3.2	
Sonneborn Penetrating Sealer 40 VOC	1	1.7	5.3	1.9	8.2	1.4	5.1	1.2	5.6	3.1 (2.0)
	2	0.9	2.6	1.7	5.7	1.5	4.3	1.8	4.6	
	3	1.5	2.6	1.4	1.8	0.8	5.6	1.5	3.0	
	4	1.3	6.4	1.5	4.1	1.5	5.3	2.0	4.2	
TK 290-WDOT	1	0.5	5.5	0.6	2.5	0.5	1.6	0.4	2.2	1.8 (1.5)
	2	0.8	3.6	0.6	1.9	0.5	1.2	0.4	2.8	
	3	0.5	1.8	0.5	3.5	0.5	1.8	0.3	4.4	
	4	0.9	3.4	0.8	2.8	0.9	4.7	0.3	4.0	
Aquatrete BSM 20	1	0.8	2.8	0.6	3.8	0.7	2.4	0.8	2.8	2.0 (1.6)
	2	0.5	2.2	0.8	4.7	0.7	3.8	0.6	1.9	
	3	0.5	2.5	0.8	3.5	0.7	2.4	0.4	3.9	
	4	0.7	6.4	0.3	2.2	0.9	3.4	0.6	3.5	
Baracade WB 244	1	1.3	3.2	0.9	4.2	1.5	2.8	0.7	3.1	2.1 (1.1)
	2	1.8	3.6	1.2	3.4	0.7	2.2	1.5	2.3	
	3	0.8	2.4	1.5	3.5	1.4	2.4	1.7	2.5	
	4	1.0	2.1	1.8	3.5	0.5	4.2	0.6	2.4	
Hydrozo Enviroseal 20	1	0.3	2.1	1.3	2.7	0.4	1.7	0.4	1.2	1.4 (0.8)
	2	0.9	1.7	0.4	1.8	0.8	1.8	0.6	1.5	
	3	1.0	3.2	0.7	1.7	0.7	2.9	0.9	2.2	
	4	1.0	1.9	0.4	2.3	0.7	2.0	0.2	2.0	
Hydrozo Enviroseal 40	1	1.6	2.9	1.8	3.7	1.4	3.6	1.7	4.3	2.1 (1.0)
	2	1.2	2.4	1.1	2.0	1.5	2.9	0.8	2.9	
	3	0.8	2.1	0.5	1.9	1.8	2.5	1.7	2.7	
	4	1.0	3.2	1.4	2.6	1.1	3.0	1.6	3.3	
Powerseal 40%	1	2.1	1.9	1.6	3.5	1.6	2.8	0.8	1.4	1.9 (1.0)
	2	0.6	1.7	0.9	2.3	1.6	1.9	1.8	2.1	
	3	0.7	3.2	1.0	3.1	1.1	2.6	1.0	1.6	
	4	0.6	4.7	1.6	3.9	1.7	2.0	0.8	1.8	

Table 6.2.6 Depth of penetration measurements, averages and standard deviations (continued)

TK 290-WB	1	0.5	2.5	0.8	4.2	1.2	3.1	0.9	3.1	1.5	(1.1)
	2	1.0	3.9	0.7	2.1	0.7	1.9	0.8	3.3		
	3	0.9	1.7	0.3	1.6	0.7	1.9	0.5	0.7		
	4	0.5	1.2	0.9	1.2	0.8	2.6	0.3	2.1		
V-Seal	1	0.5	2.7	0.4	3.0	1.9	5.8	0.6	3.3	1.7	(1.4)
	2	0.5	2.3	0.0	2.0	0.0	3.1	0.0	2.7		
	3	0.0	2.0	0.4	3.8	1.3	2.2	0.4	2.0		
	4	0.8	2.5	0.4	2.5	0.9	3.6	0.0	2.8		

* Values in parentheses show the standard deviation of the results
Note: 1 inch = 25.4 mm

A summary of the average depth of penetration and standard deviation for all sealants is shown in Table 6.2.7. It can be seen that the average depth of penetration of the sealants studied varied approximately between 1.4 mm and 3.8 mm.

Figure 6.2.11 shows the average depth of penetration for each sealant, arranged in order of decreasing value. The data show that solvent-based products generally had a higher depth of penetration than water-based products. Two exceptions were Eucoguard 100 and TK 290-WDOT which had depths of penetration smaller than some water-based products.

Table 6.2.7 Summary of average depth of penetration for all sealants

Sealant	Average Depth of Penetration (mm)	
Solvent-based:		
Aquanil Plus 40	2.5	(1.6)*
Eucoguard 100	1.8	(1.1)
Hydrozo Silane 40 VOC	3.8	(2.0)
Penseal 244	2.7	(1.5)
Sonneborn Penetrating Sealer 40 VOC	3.1	(2.0)
TK 290-WDOT	1.8	(1.5)
Water-based:		
Aqua-Trete BSM 20	2.0	(1.6)
Baracade WB 244	2.1	(1.1)
Hydrozo Enviroseal 20	1.4	(0.8)
Hydrozo Enviroseal 40	2.1	(1.0)
Powerseal 40%	1.9	(1.0)
TK 290-WB	1.5	(1.1)
V-Seal	1.7	(1.4)

* Value listed in parentheses shows the standard deviation of the results
Note: 1 inch = 25.4 mm

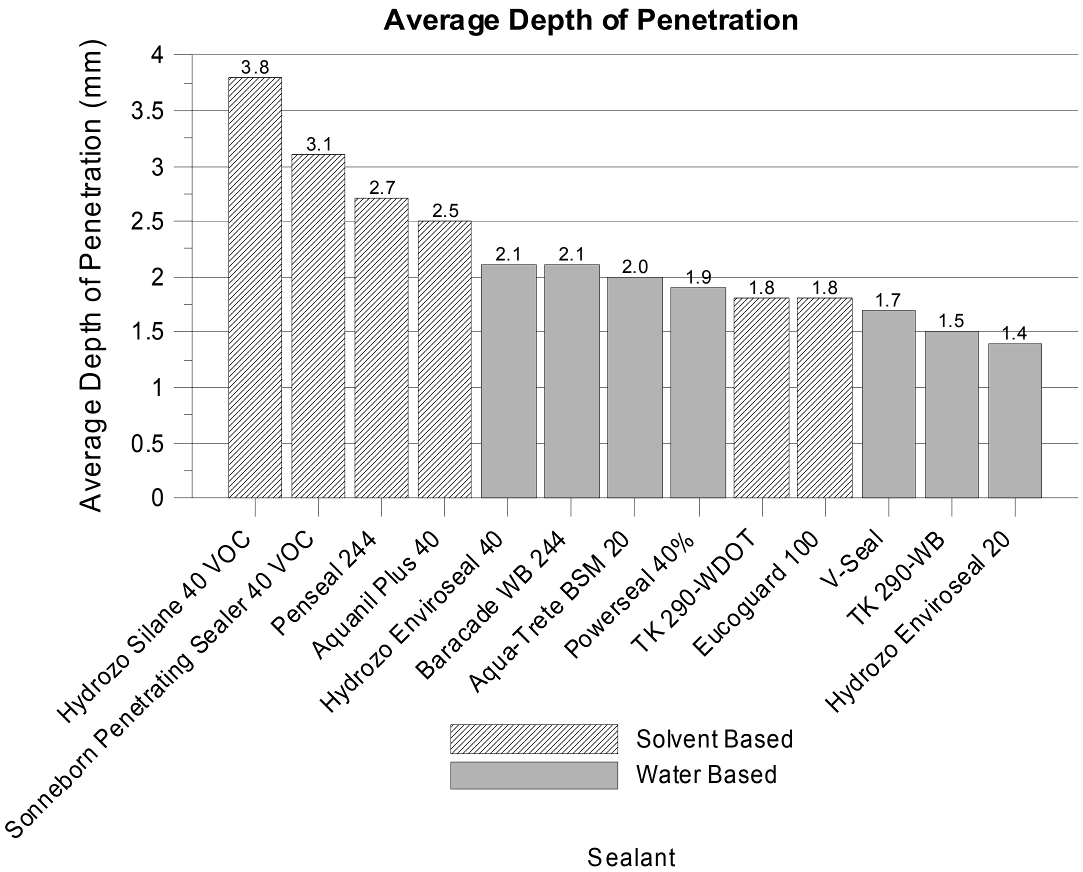


Figure 6.2.11 Average depth of penetration of each sealant arranged in order of decreasing value.

It may be noted that, the four solvent-based sealants with the largest depths of penetration (Hydrozo Silane 40 VOC, Sonneborn Penetrating Sealer 40 VOC, Penseal 244, and Aquanil Plus 40) were all silane products, while the two solvent-based products with smaller depths of penetration (TK 290-WDOT and Eucoguard 100) were both siloxanes. This trend is reasonable since silanes are the smallest molecules, and can generally penetrate further into the concrete than siloxanes, which are a bit larger (Henry, 2004).

6.3 Discussion of Test Results

6.3.1 Relationship between depth of penetration and performance

In Table 6.3.1, the average depth of penetration is compared with the manufacturer reported value for each sealant. Upon examination of the data, it is clear that none of the 13 deck sealants tested provided as much penetration as was expected based on manufacturer product data.

Each sealant listed in Table 6.3.1 was reported by the manufacturer to have a penetration depth of at least 3.2 mm (1/8 inch), which was the target sandblasting depth required by AASHTO T 259. However only one sealant, Hydrozo Silane 40 VOC had an average measured depth of penetration greater than the target sandblasting depth of 3.2 mm (1/8 inch). An additional sealant, Sonneborn Penetrating Sealer 40 VOC had an average depth of penetration of 3.1 mm, which was very close to the target sandblasting depth. Not coincidentally these were the two sealants with the best performance in deterring chloride ion intrusion when not exposed to freeze-thaw cycles.

Table 6.3.1 Measured and manufacturer reported depth of penetration

Sealant	Depth of Penetration		
	Average Measured (mm)		Manufacturer Reported (mm)
Solvent-based:			
Aquanil Plus 40	2.5	(1.6)*	unknown
Eucoguard 100	1.8	(1.1)	7.6 – 10.2
Hydrozo Silane 40 VOC	3.8	(2.0)	5.0
Penseal 244	2.7	(1.5)	3.2 – 6.4
Sonneborn Penetrating Sealer 40 VOC	3.1	(2.0)	5.0
TK 290-WDOT	1.8	(1.5)	3.2 –6.4
Water-based:			
Aqua-Trete BSM 20	2.0	(1.6)	3.2 – 6.4
Baracade WB 244	2.1	(1.1)	9.5
Hydrozo Enviroseal 20	1.4	(0.8)	3.6
Hydrozo Enviroseal 40	2.1	(1.0)	6.1
Powerseal 40%	1.9	(1.0)	3.2 –6.4
TK 290-WB	1.5	(1.1)	3.2 – 6.4
V-Seal	1.7	(1.4)	19.1 – 25.4

* Value in parentheses shows the standard deviation of the results

Note: 1 inch = 25.4 mm

Table 6.3.2 shows a comparison between the depth of penetration and the ratio of absorbed chloride for all sealants. The sealants are arranged in order of increasing performance to deter chloride ion intrusion. Only data from specimens not exposed to freeze-thaw cycles are shown. Ideally, the data would be expected to follow an inverse trend, i.e., sealants with the largest depth of penetration would be expected to have the smallest ratio of absorbed chloride, and vice versa. While the data in this table do not follow this trend exactly, it is seen that, in general, the sealants that offered the best protection also had the largest depths of penetration. For example, the data in Table 6.3.2 show that the four sealants with the lowest ratios of absorbed chloride content had the largest depths of penetration. It should be noted that although the average depth of penetration of these sealants didn't always exceed the target sandblasting depth of 3.2 mm (1/8 inch, except for Hydrozo Silane 40 VOC), they all exceeded the lower limit of sandblasting depth of 1.6 mm (1/16 inch) allowed by AASHTO T 259. In addition, these sealants had average depths of penetration at least 0.4 mm larger than any other sealant, and had ratios of absorbed chloride at least 0.2 less than all other sealants.

Sealants five through nine in Table 6.3.2 provided some level of protection against chloride ion intrusion. These five sealants had ratios of absorbed chloride between 0.77 and 0.88 and depths of penetration between 1.7 and 2.1 mm. The performance of these sealants was likely limited by their depths of penetration, which exceeded the lower limit of sandblasting depth mentioned above of 1.6 mm, but was much smaller than the target sandblasting depth of 3.2 mm. Had these sealants not been subjected to as much or any abrasion, i.e., sandblasting, they could have performed much better.

The last four sealants in Table 6.3.2, Hydrozo Enviroseal 20, TK 290-WB, Baracade WB 244 and Eucoguard 100 provided virtually no protection compared to unsealed concrete and had depths of penetration far below the target sandblasting depth. Table 6.3.2 shows that Hydrozo Enviroseal 20 and TK 290-WB had average depths of penetration less than 1.6 mm, the lower limit of sandblasting depth allowed by AASHTO T 259. Close examination of the data in Table 6.2.6 shows that Hydrozo Enviroseal 20 and TK 290-WB were able to penetrate beyond 1.6 mm in some areas, but in other areas had virtually no penetration. The very shallow depth of penetration of these two sealants serves to explain their poor performance. Eucoguard 100 and Baracade WB 244 were able to penetrate slightly more, but the products themselves were unable to protect the concrete from chloride ion intrusion. Overall, the performance of these sealants was poor with respect to unsealed concrete.

Table 6.3.2 Comparison between average depth of penetration and ratio of absorbed chloride in specimens not exposure to F/T cycles

	Sealant	**Ratio of Absorbed Chloride** (without exposure to F/T cycles)	**Average Depth of Penetration** (mm)
1	Hydrozo Silane 40 VOC	0.37	3.8
2	Sonneborn Penetrating Sealer 40 VOC	0.46	3.1
3	Aquanil Plus 40	0.50	2.5
4	Penseal 244	0.57	2.7
5	Powerseal 40%	0.77	1.9
6	V-Seal	0.77	1.7
7	Aqua-Trete BSM 20	0.84	2.0
8	TK 290-WDOT	0.86	1.8
9	Hydrozo Enviroseal 40	0.88	2.1
10	Hydrozo Enviroseal 20	1.05	1.4
11	TK 290-WB	1.11	1.5
12	Baracade WB 244	1.11	2.1
13	Eucoguard 100	1.27	1.8

Note: 1 inch = 25.4 mm

To further examine the relationship between depth of penetration and performance, additional chloride ion analysis tests were performed on non-sandblasted specimens treated with three sealants, but without exposure to freeze-thaw cycles. The sealants used in these tests were TK 290-WDOT, Baracade WB 244 and V-Seal. Table 6.3.3 shows the average and standard deviation of the absorbed chloride content in these specimens. The data show that TK 290-WDOT and Baracade WB 244 provided full protection against chloride ion intrusion. (Note that the performance of these sealants was marginal to poor when the specimens were sandblasted – see Table 6.3.2.) V-Seal was not as effective, but absorbed less than half of the chloride of the unsealed specimens.

Table 6.3.3 Average absorbed chloride in sealed specimens without sandblasting

Sealant	Absorbed Chloride -- ***Sealed*** Specimens (lb Cl$^-$/yd^3) [1]	Absorbed Chloride -- ***Unsealed*** Specimens (lb Cl$^-$/yd^3) [2]	***Sealed/Unsealed*** [1]/[2]
TK 290-WDOT	0.00 (0.23)*	2.42 (0.97)	0.00
Baracade WB 244	0.00 (0.25)	2.42 (0.97)	0.00
V-Seal	1.03 (1.02)	2.42 (0.97)	0.43

* Values in parentheses show the standard deviation of the results

These results further corroborate the relationship between the ability of the sealants to deter chloride ion intrusion and their depth of penetration, and suggest that these and other sealants could perform much better with no or less abrasion. There exists a wide range of opinions concerning the realistic depth of abrasion of bridge decks. The depth of abrasion required by AASHTO T 259 may be too severe and not indicative of the actual abrasion encountered in in-service bridge decks, especially for decks with low volume traffic. During this research, no studies were found that examined the amount of abrasion that occurs on in-service bridge decks, but this aspect should be evaluated in future studies.

The data also suggest that sealants with lower depths of penetration can perform well and perhaps should be allowed provided that they are applied more frequently to ensure that a sufficient layer of sealant remains present on the deck. Such an alternative may prove to be viable, especially when the use of a sealant with lower penetration depth leads to a lower cost and allows a significant reduction in the time to open to traffic. Future studies should include tests with various abrasion depths, and should seek to establish a better correlation between the actual abrasion in bridge decks and that specified in the tests.

6.3.2 Effect of freeze-thaw cycles

A summary of the average absorbed chloride ratio for all specimens, with and without exposure to freeze-thaw cycles is shown in Figure 6.3.1. The data show that freeze-thaw cycles decreased the sealants ability to deter chloride ion intrusion for nearly all the sealants. In particular, the ratio of absorbed chloride for specimens with Aquanil Plus 40 increased nearly three times when exposed to freeze-thaw cycles. A few sealants however, displayed nearly the same ratio of absorbed chloride content whether they were exposed to freeze-thaw cycles or not. Examples of sealants which were essentially unaffected by freeze-thaw cycles are Sonneborn Penetrating Sealer 40 VOC, V-Seal, Aqua-Trete BSM 20, and Hydrozo Enviroseal 20.

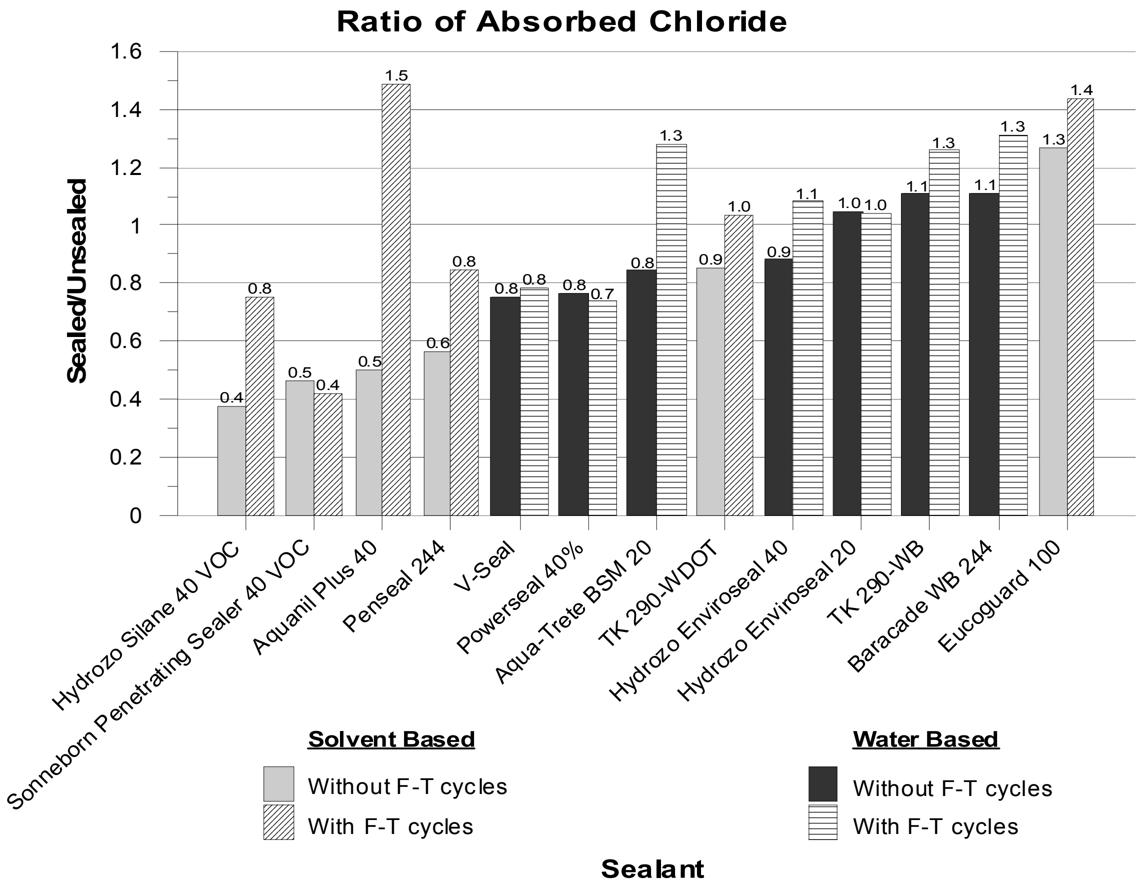


Figure 6.3.1 Average absorbed chloride ratio for all sealants, with and without exposure to freeze-thaw cycles.

6.3.3 WisDOT acceptance criteria

The acceptance criterion for penetrating sealants used by the WisDOT is based on a ratio between the absorbed chloride of sealed versus unsealed specimens, as described in section 3.2.1. The WisDOT acceptance criteria equations are repeated below:

$$Cl^{-}_{sealed} \le \left(\frac{Cl^{-}_{unsealed} - Cl^{-}_{control}}{2} \right) + Cl^{-}_{control} \qquad \textbf{[3-1]}$$

The above equation can be rearranged and the acceptance criterion can also be displayed as:

$$Cl^{WisDOT}_{content} \equiv \frac{Cl^{-}_{sealed}}{Cl^{-}_{unsealed} + Cl^{-}_{control}} \le 0.5 \qquad \textbf{[3-2]}$$

In other words, a sealant with a chloride content ratio, $Cl^{WisDOT}_{content}$, less than or equal to 0.5 would be accepted. It should be noted that the chloride content ratio, $Cl^{WisDOT}_{content}$, defined by equation (3-2), is also a measure of the chloride content absorbed by specimens, but its numerical value is different from the ratio of absorbed chloride presented earlier in section 6.2.2.2a.

6.3.3.1 Chloride content ratio of sealants not subjected to freeze-thaw cycles

Table 6.3.4 shows the chloride content ratio for deck sealants not exposed to freeze-thaw cycles. The results show that three sealants have chloride content ratios less than or equal to 0.50. These are: Hydrozo Silane 40 VOC, Sonneborn Penetrating Sealer 40 VOC, and Aquanil Plus 40 which have chloride content ratios of 0.42, 0.46, and 0.50 respectively. Therefore, these are the only sealants that would be accepted per the WisDOT acceptance criteria.

Table 6.3.4 Chloride content ratio for specimens not exposed to freeze-thaw cycles

Sealant	Total Chloride -- ***Control*** Specimens (lb Cl^-/yd^3)	Total Chloride -- ***Sealed*** Specimens (lb Cl^-/yd^3)	Total Chloride -- ***Unsealed*** Specimens (lb Cl^-/yd^3)	$Cl^{WisDOT}_{content}$
Solvent-based:				
Aquanil Plus 40	1.45	2.86	4.26	0.50
Eucoguard 100	1.45	5.01	4.26	0.88
Hydrozo Silane 40 VOC	1.28	2.87	5.52	0.42
Penseal 244	1.69	3.92	5.63	0.54
Sonneborn Penetrating Sealer 40 VOC	1.28	3.12	5.52	0.46
TK 290-WDOT	1.22	6.15	6.98	0.75
Water-based:				
Aqua-Trete BSM 20	1.22	6.07	6.98	0.74
Baracade WB 244	1.46	7.11	6.55	0.89
Hydrozo Enviroseal 20	1.44	6.27	6.05	0.84
Hydrozo Enviroseal 40	1.44	5.49	6.05	0.73
Powerseal 40%	1.47	4.73	5.73	0.66
TK 290-WB	1.46	7.10	6.55	0.89
V-Seal	1.69	4.73	5.63	0.65

Figure 6.3.2 shows the chloride content ratio for each sealant, arranged in decreasing order of performance. It is apparent that solvent-based products tended to perform better than water-based products using the WisDOT acceptance criteria given in equations 3-1 and 3-2 above. This observation agrees with the results from the depth of penetration test and from the ratio of absorbed chloride as computed in 6.2.2.2a for specimens not exposed to freeze-thaw cycles.

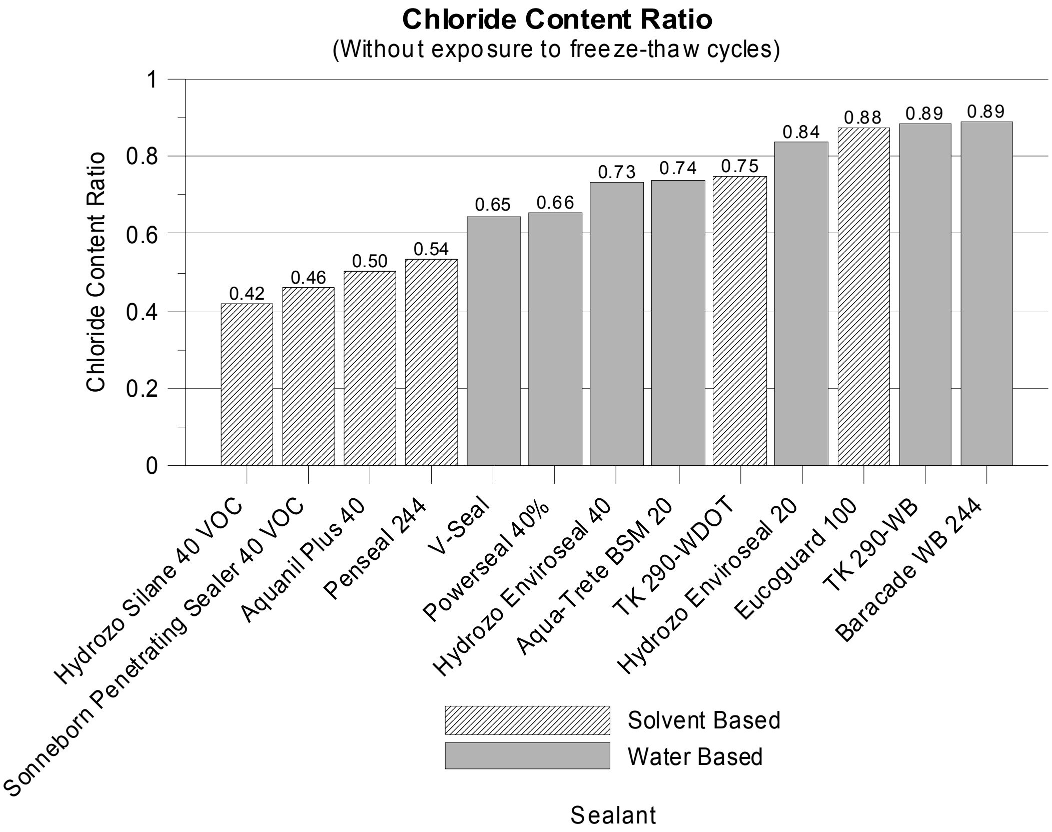


Figure 6.3.2 Chloride content ratio for specimens not subjected to freeze-thaw cycles based on WisDOT acceptance criteria

6.3.3.2 Chloride content ratio of sealants subjected to freeze-thaw cycles

Equation (3-2) was developed as an acceptance criterion for sealants tested in specimens without exposure to freeze-thaw cycles. In this section, the same equation is used to evaluate the performance of the sealants subjected to freeze-thaw cycles. However, since the specimens exposed to freeze-thaw cycles were cast from a different batch than those without exposure, minor differences in the chloride content of the mix itself from different batches needed to be considered in the calculations. The procedure used to account for these differences is shown in Appendix D.

Table 6.3.5 shows the total chloride content for the control and sealed specimens subjected to freeze-thaw cycles, as well as the total chloride content of the unsealed specimens no subjected to freeze-thaw cycles. The ratio of chloride content, $Cl_{content}^{WisDOT}$, between the sealed and unsealed specimens is shown in the last column of the table. This ratio is also shown in Figure 6.3.3. It is clear from this figure that there was no performance

Table 6.3.5 Chloride content ratio for specimens exposed to freeze-thaw cycles

Sealant	Total Chloride -- ***Control*** Specimens (lb Cl^-/yd^3)	Total Chloride -- ***Sealed*** Specimens (lb Cl^-/yd^3)	Total Chloride -- ***Unsealed*** Specimens* (lb Cl^-/yd^3)	$Cl^{WisDOT}_{content}$
Solvent-based:				
Aquanil Plus 40	1.27	5.98	4.08	1.12
Eucoguard 100	1.27	5.82	4.08	1.09
Hydrozo Silane 40 VOC	1.60	4.30	5.84	0.58
Penseal 244	1.39	5.23	5.32	0.78
Sonneborn Penetrating Sealer 40 VOC	1.60	3.11	5.84	0.42
TK 290-WDOT	1.37	7.02	7.14	0.83
Water-based:				
Aqua-Trete BSM 20	1.37	8.36	7.14	0.98
Baracade WB 244	1.52	8.03	6.61	0.99
Hydrozo Enviroseal 20	1.54	6.12	6.15	0.80
Hydrozo Enviroseal 40	1.54	6.30	6.15	0.82
Powerseal 40%	1.72	4.49	5.98	0.58
TK 290-WB	1.52	7.77	6.61	0.96
V-Seal	1.39	4.95	5.32	0.74

* Total absorbed chloride from specimens not exposed to freeze-thaw cycles (See Appendix D)

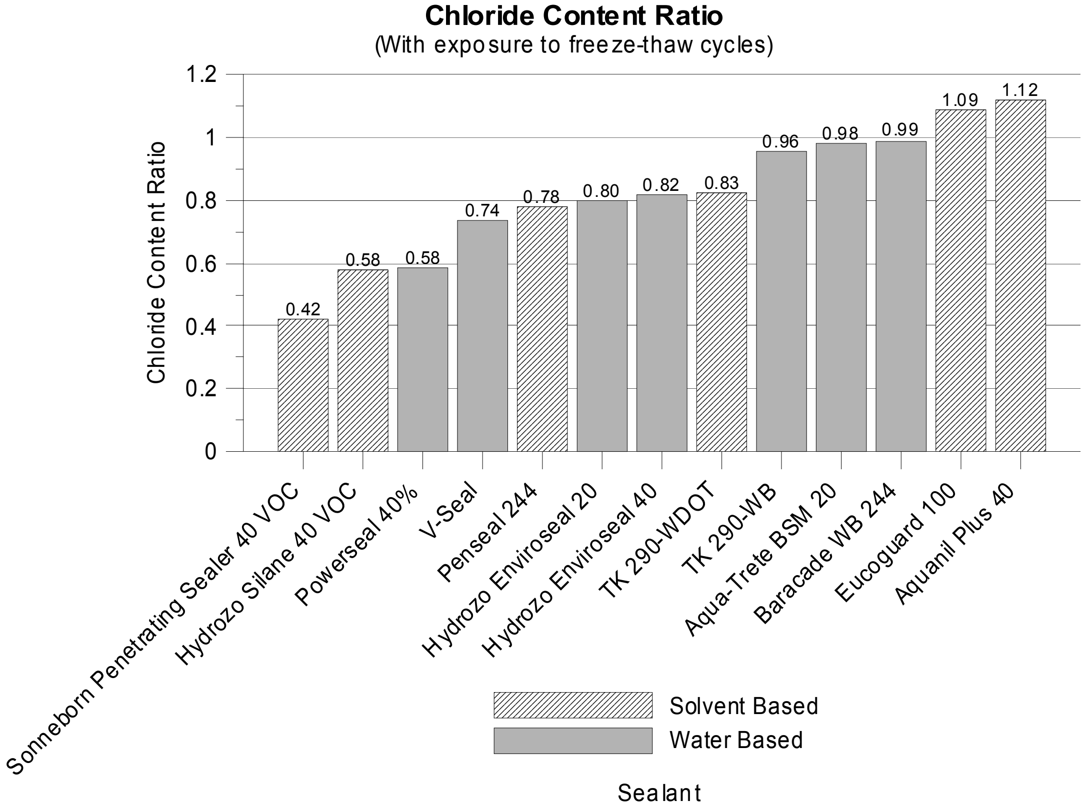


Figure 6.3.3 Chloride content ratio for specimens subjected to freeze-thaw cycles based on WisDOT acceptance criteria.

distinction between solvent and water-based products when considering specimens subjected to freeze-thaw cycles, which agrees with the observation made earlier in section 6.2.2.2b based on the ratio of absorbed chloride for specimens exposed to freeze-thaw cycles.

The chloride content ratios for two of the three sealants meeting the WisDOT acceptance criteria when not exposed to freeze-thaw cycles, Aquanil Plus 40 and Hydrozo Silane 40 VOC, increased beyond the point of acceptance when they were exposed to freeze-thaw cycles. The chloride content ratio for Aquanil Plus 40 more than doubled when exposed to freeze-thaw cycles, increasing from 0.50 to 1.12. The increase in the chloride content ratio of Hydrozo Silane 40 VOC was more moderate, from 0.42 to 0.58. The chloride content ratio for Sonneborn Penetrating Sealer when exposed to freeze-thaw cycles slightly decreased when exposed to freeze-thaw cycles, from 0.46 to 0.42. Given the scatter observed in the data and large standard deviations, it may be concluded that the performance of Sonneborn Penetrating Sealer 40 VOC was virtually unaffected by exposure to freeze-thaw cycles. Therefore, Sonneborn Penetrating Sealer 40 VOC would, in rigor, be the only sealant to meet the WisDOT acceptance criteria when exposed to freeze-thaw cycles.

6.3.4 Reduction of data scatter

Results from a previous study (Bush, 1998) showed that the AASHTO T 259/260 test procedure is associated with a great deal of scatter, i.e., large standard deviations with respect to the average. Likewise, the results from this study shown in section 6.2.2.2 also indicate large standard deviations associated with the chloride ion test.

Recognizing that there is a relationship between a sealant's depth of penetration and its performance, it is apparent that scatter observed in the absorbed chloride is directly related to the variability observed in the penetration depth (see Figure 6.2.9). The variability in sealant penetration, combined with even minor variations in sandblasting depth will result in significant scatter in the data. The standard deviations for the measured depths of penetration were generally large with respect to the average depth of penetration – between 48 and 83% of the mean. The standard deviations were equally large for the absorbed chloride, ranging from 15 to 90% of the mean.

A possible approach to reducing the large scatter of the data is to test more samples from each block of concrete with a given sealant. In this study, each sealant was applied to three concrete blocks, in accordance with the AASHTO T 259 standard, and three holes were drilled from each block in accordance with the procedure conducted by the WisDOT Materials Laboratory (the AASHTO T 259/260 standards have no requirements for the number of holes to be drilled in each block.)

To assess the influence of additional measurements in reducing the scatter of the data, additional measurements were taken from specimens treated with one sealant, Sonneborn Penetrating Sealer 40 VOC. These measurements were taken from three additional holes drilled in each of the three concrete blocks, for a total of 18 holes (six holes per block, three blocks per sealant). In Table 6.3.6, the average chloride ion content and standard deviation based on three holes per block (two samples per hole), along with a revised average and standard deviation that includes measurements from the three additional holes are compared.

It may be seen that by doubling the number of holes, the standard deviation as a percent of the average decreased by nearly 10%. Increasing the number of holes tested per sealant improves the quality and reliability of the results obtained, and should be considered a dependable and simple method for reducing the scatter of the data. However, the extra time and effort required to test additional samples should be considered and weighed against the benefit of reducing the standard deviation when selecting the number of samples to test.

Table 6.3.6 Summary of results from additional chloride ion analysis tests performed on Sonneborn Penetrating Sealer 40 VOC

Number of Holes/Block	Average Absorbed Chloride -- Sealed Specimens (lb Cl^-/yd^3)	Standard Deviation as a % of the Average Absorbed Chloride
Previous - 3 samples/block	1.96 (1.17)*	60%
Revised - 6 samples/block	1.84 (0.93)	51%

* Values in parentheses show the standard deviation of the results

6.3.5 Sealant performance evaluation

In section 3.3.1, the methods used in the preliminary evaluation to review and rank deck sealants in terms of their expected performance were described. The main characteristics of the products were recorded and divided into a variety of categories. These included surface preparation requirements, environmental application conditions, expected durability, time to open traffic, and coverage rate and cost. The products were assigned a score between 1 and 10 in each category, with 10 representing the most desirable quality.

The assigned score was weighed differently according to the relative importance of each category, and a composite score was computed for each product, as shown in Table 3.3.2.

Table 6.3.7 summarizes the results of the different performance criteria used to evaluate the deck sealants. The number in parentheses after the sealant name indicates the rank of the product based on the composite score computed during the preliminary evaluation for the sealants (see section 3.3.1). In the table, sealants with comparable performance were assigned to a given performance group category defined as follows. Those exhibiting the best performance were assigned to category I, while the sealants with the lowest performance were assigned to category III. Sealants with moderate performance were assigned to category II.

Table 6.3.7 Ratio of absorbed chloride, chloride content ratio and average depth of penetration of the deck sealants

Sealant	Ratio of Absorbed Chloride		$Cl_{content}^{WisDOT}$		Average Depth of Penetration (mm)	Performance Group Category
	Not Exposed to F/T Cycles	Exposed to F/T Cycles	Not Exposed to F/T Cycles	Exposed to F/T Cycles		
Sonneborn Penetrating Sealer 40 VOC (6)*	0.46	0.42	0.46	0.42	3.1	I
Hydrozo Silane 40 VOC (9)	0.37	0.75	0.42	0.58	3.8	
Powerseal 40% (11)	0.77	0.74	0.66	0.58	1.9	II
V-Seal (2)	0.77	0.78	0.65	0.74	1.7	
Penseal 244 (8)	0.57	0.85	0.54	0.78	2.7	
TK 290-WDOT (4)	0.86	1.04	0.75	0.83	1.8	
Hydrozo Enviroseal 40 (12)	0.88	1.08	0.73	0.82	2.1	
Aqua-Trete BSM 20 (3)	0.84	1.28	0.74	0.98	2	
TK 290-WB (5)	1.11	1.26	0.89	0.96	1.5	III
Hydrozo Enviroseal 20 (10)	1.05	1.04	0.84	0.8	1.4	
Baracade WB 244 (7)	1.11	1.31	0.89	0.99	2.1	
Eucoguard 100 (13)	1.27	1.44	0.88	1.09	1.8	
Aquanil Plus 40 (1)	0.5	1.49	0.5	1.12	2.5	

* The number in parentheses indicates the product rank based on the composite score computed in section 3.3.1

Sonneborn Penetrating Sealer 40 VOC and Hydrozo Silane 40 VOC offered the best protection to the concrete among the sealants tested in this study and were assigned to Performance Group Category I. These sealants exhibited consistently good performance compared to other sealants throughout all of the tests. Although their rank based on product characteristics was not particularly high (number in parentheses in Table 6.3.7), the Sonneborn Penetrating Sealer performed well and was unaffected by the exposure to freeze-thaw cycles. Hydrozo Silance 40 VOC offered the most protection to the concrete when not exposed to freeze-thaw cycles. Although exposure to freeze-thaw cycles decreased its effectiveness, it still offered good protection to the concrete. Additionally, these two sealants had the largest average depths of penetration, either very close to or exceeding the 3.2 mm (1/8 inch) target sandblasting depth required by AASHTO T 259.

The next group of sealants, Powerseal 40%, V-Seal, Penseal 244, TK 290-WDOT, Hydrozo Enviroseal 40 and Aqua-Trete BSM 20, were assigned to Performance Group Category II. In general, these sealants were able to offer moderate protection to the concrete, but they were more adversely affected by exposure to freeze-thaw cycles. Furthermore, these sealants had shallower depths of penetration (between 1.7 and 2.7 mm). These sealants were able to penetrate beyond the *minimum* sandblasting depth required by AASHTO T 259 (1.6 mm), but were unable to penetrate as deep as the target sandblasting depth (3.2 mm). The relatively low penetration depth and the large abrasion depth required in AASHTO T 259 appeared to be the key factors limiting the performance of these sealants in this study. These sealants could still be used but they may need to be applied more frequently, in particular when significant abrasion of the deck is expected due to high volume traffic. It may also be noted that V-Seal, Aqua-Trete BSM 20 and TK 290-WDOT were ranked highly based on the preliminary evaluation. The high rankings of these products were largely due to short times to open to traffic and low materials costs, which may make them viable options for some projects.

The remaining sealants in Table 6.3.7 offered the least protection and were assigned to Performance Group Category III. Of these sealants, TK 290-WB, Hydrozo Enviroseal 20, Baracade WB 244, and Eucoguard 100 provided no protection compared to unsealed concrete, even when they were not exposed to freeze-thaw cycles. Aquanil Plus 40 performed very well when not exposed to freeze-thaw cycles, but its performance sharply declined when exposed to freeze-thaw cycles. The average penetration depth of the sealants ranged from 1.4 to 2.5 mm, so clearly some of the sealants were not able to penetrate to the minimum depth of abrasion required by AASHTO T 259.

Considering the information given above, however, the sealant chosen for an individual bridge deck should still meet the specific needs of the project. Additionally, some aspects of this test program were very severe, particularly the depth of material removed by abrasion in accordance with AASHTO T 259, and the duration and conditions of the freeze-thaw cycle tests. Therefore, the results obtained from the laboratory tests may represent worst case scenarios rather than the typical situation encountered in the field.

Chapter 7

Crack Sealants – Test Results and Discussion

7.1 Introduction

In this chapter, results of the tests conducted on the crack sealants are presented and discussed. These results include the data obtained from the depth of penetration and bond strength and durability tests. Based on the analysis of the test data and their performance, the sealants are ranked and assigned to a performance group category.

7.2 Test Results

7.2.1 Measured concrete properties

As described in section 5.3.1, the fresh air content and slump were measured for each batch of concrete. The values of fresh air content and slump for each batch of concrete used in the crack sealant test program are given in Table 7.2.1. All of the values for the fresh air content ranged between 6.1 and 6.9 percent, which was within the range of acceptable air contents of five to seven percent for the given mix design. Likewise, the results from the slump test ranged from 2.38 inches to 3.63 inches, which fell within the acceptable range of two to four inches for the given mix design.

Similar to the concrete used in the deck sealant test program, compressive strength tests were performed at age 28 days on the three 4 in. by 8 in. cylinders cast from each batch of concrete used in the crack sealant test program. The purpose of the cylinder compressive strength tests was to verify that the concrete used in the test program met the strength requirements of Grade D concrete used for concrete bridge decks. Grade D concrete has a design compressive strength of 4,000 psi according to the Wisconsin Bridge Manual.

The results from the compressive strength tests are shown in Table 7.2.1. The last column in Table 7.2.1 gives the batch average strength and standard deviation. The overall average strength for all batches cast for the crack sealant test program was 6,168 psi with a standard deviation of 591 psi. Figure 7.2.1 provides a plot of the compressive strength for each cylinder, and Figure 7.2.2 shows a plot of the batch average compressive strength for all crack sealant concrete. Both figures indicate that the results were very consistent, with only one obvious outlier in batch one with a compressive strength of 3,720 psi. All other cylinders easily exceeded the design compressive strength of 4,000 psi.

Table 7.2.1 Measured concrete properties for crack sealant concrete

Batch	Fresh Air Content (%)	Slump (in.)	Compressive Strength Data			
			Cylinder #	Strength (psi)	Batch Average Strength (psi)	
1	6.7	3.25	1	3720	5875**	(742)*
			2	6400		
			3	5350		
2	6.5	2.375	4	6640	6580	(56)
			5	6570		
			6	6530		
3	6.5	3.25	7	6660	6527	(378)
			8	6820		
			9	6100		
4	6.9	3.25	10	5290	5973	(605)
			11	6190		
			12	6440		
5	6.9	3.5	13	5640	6220	(503)
			14	6480		
			15	6540		
6	6.5	3.25	16	6220	6207	(121)
			17	6080		
			18	6320		
7	6.9	3.5	19	6180	6140	(154)
			20	6270		
			21	5970		
8	6.4	3.25	22	6070	6037	(31)
			23	6030		
			24	6010		
9	6.3	3.25	25	6750	6713	(158)
			26	6850		
			27	6540		
10	6.1	3.0	28	6840	6710	(114)
			29	6630		
			30	6660		
11	6.6	3.0	31	5930	6127	(179)
			32	6170		
			33	6280		
12	6.9	3.625	34	5790	5630	(155)
			35	5480		
			36	5620		

* Values in parentheses show the standard deviation of the results

** Batch one average compressive strength and standard deviation based on cylinders 2 and 3 only

The compressive strength data combined with the results of the fresh air content and slump tests show that there was little variation in the measured properties of the concrete batches. The measured concrete strengths were all above the minimum required except for one outlier (see Fig. 7.2.1).

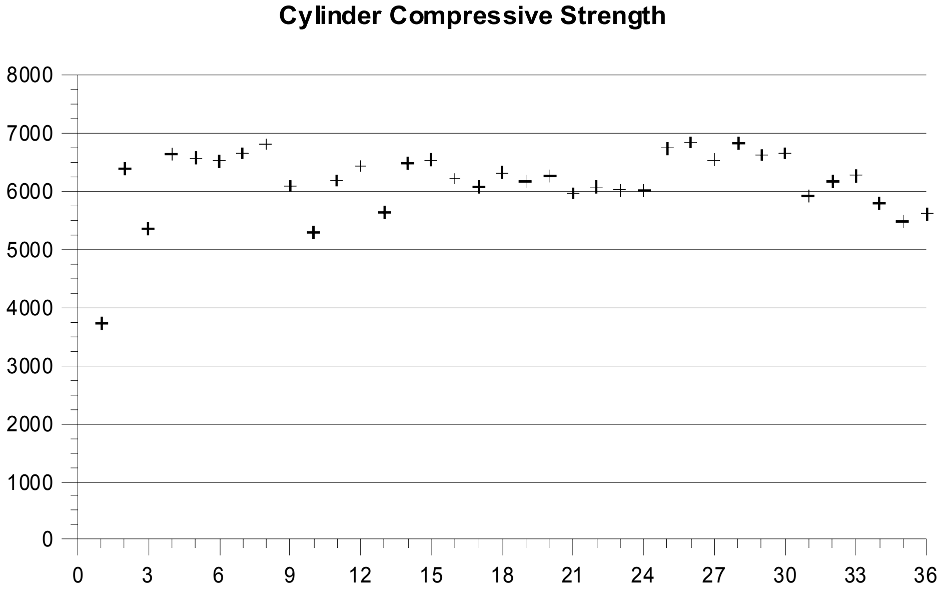


Figure 7.2.1 Cylinder compressive strength of the concrete used in specimens with crack sealants.

concrete

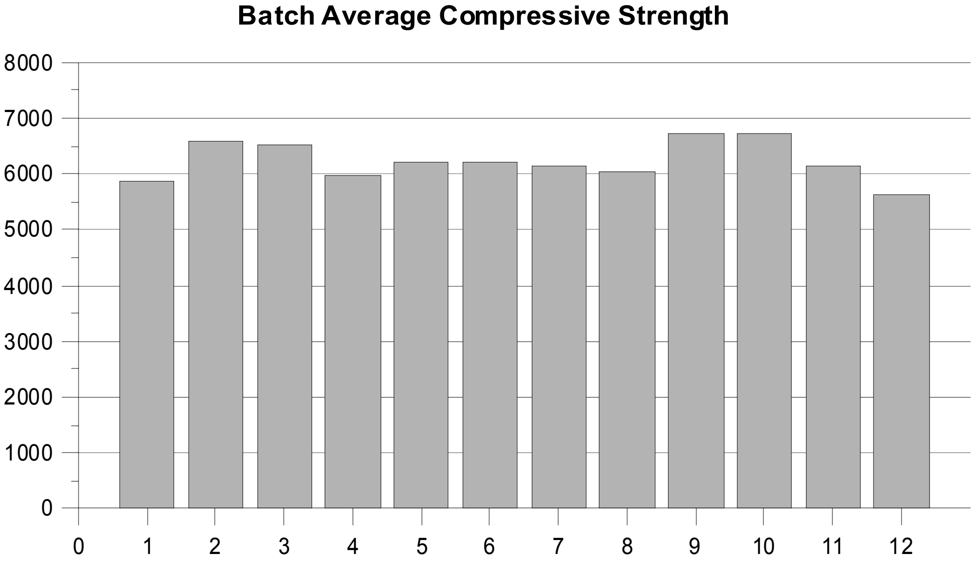


Figure 7.2.2 Batch average compressive strength of the concrete used in specimens with crack sealants.

7.2.2 Depth of penetration tests

The depth of penetration of the crack sealants was measured by visually examining both with the naked eye and with a measuring magnifier. Two cross sections of each specimen were inspected and the maximum depth of penetration was measured for each. All sealants were able to penetrate the full depth of the crack, 2 ½ inches, irrespective of the crack width. Most specimens, however, exhibited small voids or air pockets (approximately 0.03 in. or less in length, width, or diameter) within the sealant, or between the sealant and the adjacent face of the crack.

Characteristics of the voids within or adjacent to the sealant were recorded to determine whether the size or frequency of the voids was related to the bond strength. The depth at which the first small void or air pocket appeared within each of the four specimens examined at each crack width category for each sealant is given in Table 7.2.2. Additionally, a second void depth is given in Table 7.2.2 if it was significantly different in size or shape from the first void. Hatched areas in Table 7.2.2 indicate that a sealant was not tested at that crack width, so no depth of penetration observations were made.

7.2.3 Bond strength and durability tests

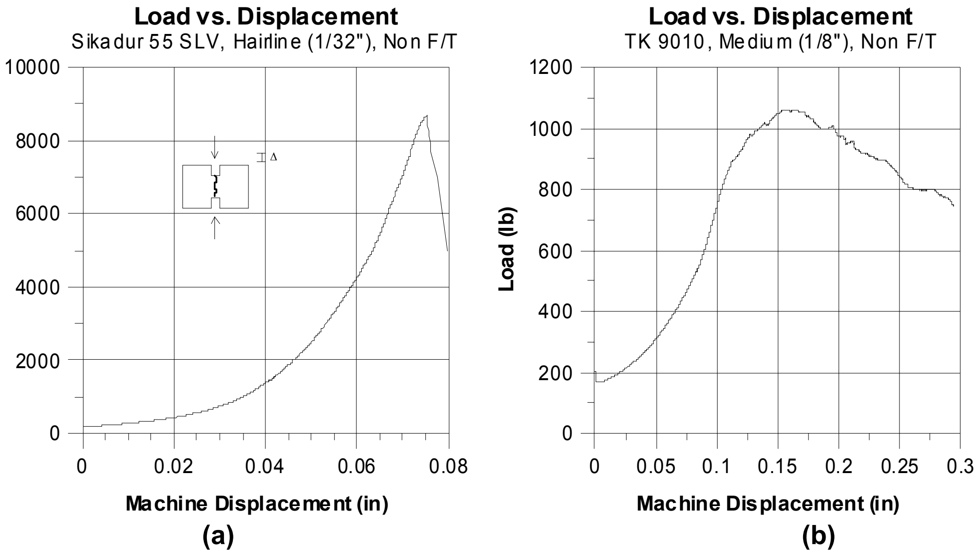
Figure 7.2.3 shows sample load versus displacement plots for two different sealants at two different crack widths. The figure serves to illustrate that significantly different behavior occurred between these two sealants, where Sikadur 55 SLV showed high bond strength and small displacements, and TK 9010 showed very low bond strength with substantial displacement before reaching its peak resistance.

Several failure modes were observed during the tests. The failure modes were divided into three basic categories as follows: concrete failure, bond failure, or sealant failure. A concrete failure was indicated by cracks primarily in concrete adjacent to the sealed crack. An example of a concrete failure is shown in Figure 7.2.4. A bond failure was indicated by cracks in the sealant-concrete interface, i.e., between the sealant and the concrete immediately adjacent to it. An example of a bond failure is given in Figure 7.2.5. A sealant failure was indicated by cracks passing directly through the sealant without involvement of the adjacent concrete. An example of a sealant failure is given in Figure

7.2.6. Additionally, bond strength failures involving combinations of any of the aforementioned failure modes were also observed.

Table 7.2.2 Depth of first voids for crack sealer specimens

	Depth of Voids (in)			
Crack Sealer	**Hairline (< 0.06")**	**Narrow (0.06" - 0.1")**	**Medium (0.1" - 0.19")**	**Wide (> 0.2")**
Degadeck Crack Sealer	1/4, 1/2	3/16	1/8, 7/8	▨
	3/4, 1.0	1/8, 7/8	5/8, 1 1/4	▨
	1/8	3/16	1/16	▨
	3/16	7/16	3/4	▨
Denedeck Crack Sealer	3/8	1/2, 2.0	7/8	▨
	3/8	3/4	3/4	▨
	3/16	1/2	1/2	▨
	5/16	3/4	1.0	▨
TK-9030	▨	1 3/16	▨	▨
	▨	1 5/16	▨	▨
	▨	Top of crack	▨	▨
	▨	5/16	▨	▨
TK-9010	▨	▨	7/8	▨
	▨	▨	No voids	▨
	▨	▨	1/2	▨
	▨	▨	1/2	▨
SikaPronto 19	1/4	7/16	3/16	▨
	1/16	5/8	3/8	▨
	3/16	1/4	1/8	▨
	1/4	1.0	1/4	▨
Sikadur 55 SLV	1 1/4	No voids	1 1/2	▨
	1 3/8	13/16	No voids	▨
	1.0	No voids	3/8	▨
	No voids	No voids	No voids	▨
Sikadur 52	1/16	3/4	1 3/16	▨
	3/8	1/4	1.0	▨
	5/16	7/16, 1 1/4	2 1/8	▨
	Top of crack, 5/16	1/4, 1 1/4	3/8	▨
Dural 335	Top of crack	▨	▨	▨
	5/8	▨	▨	▨
	1/2	▨	▨	▨
	3/4	▨	▨	▨
TK-9000	▨	7/8, 1 5/8	1/2	3/8, 1 1/2
	▨	7/8	7/16	15/16
	▨	Top of crack, 1/2	1/2	Bottom of crack
	▨	Top of crack, 1.0	5/16, 7/8	9/16
Duraguard 401	1/2	1 1/8	1 3/4	1/4
	1/2, 7/8	3/4	No voids	3/8
	3/4, 2	7/8, 1 9/16	1 3/4	7/16
	1 5/8	1/8, 1 1/4	1/2	Top of crack, 1/4



(a) (b)

Figure 7.2.3 Load vs. displacement plots for two different sealants with two different crack widths

Figure 7.2.4 Example of a concrete failure during a bond strength test

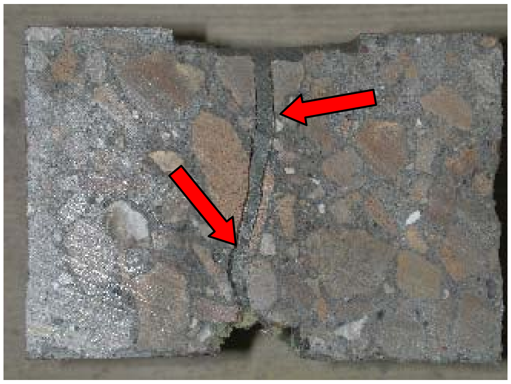


Figure 7.2.5 Example of a bond failure during a bond strength test

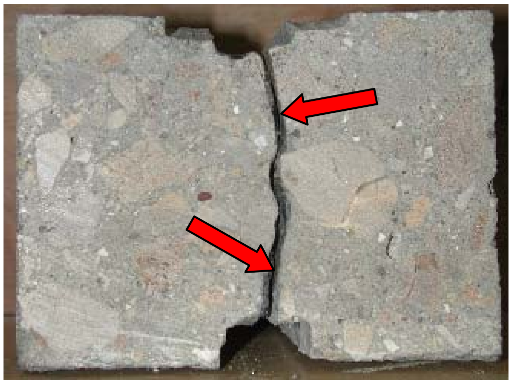


Figure 7.2.6 Example of a sealant failure during a bond strength test

7.2.3.1 Hairline crack width series (1/32")

The results of the bond strength tests for all sealants tested with hairline crack widths are shown in Table 7.2.3. For comparison, the table shows the results for specimens not exposed as well as those exposed to freeze-thaw cycles. Also shown in the table is observed failure mode. The results show that there was a significant variation in strength among sealants tested with hairline crack widths. The average strength ranged from 3,545 lbs. to 8,560 lbs. for specimens not exposed to freeze-thaw cycles, while the average strength for specimens subjected to freeze-thaw cycles ranged from no strength up to 6,599 lbs. The last column in the table shows the average percent reduction in bond strength with respect to the value measured for the specimens not exposed to freeze-thaw cycles. It can be seen that most sealants experienced a 20-30% decrease in bond strength after being subjected to freeze-thaw cycles. One sealant (Sikadur 52) showed a 48% reduction, and Duraguard 401 showed total loss of strength.

Figure 7.2.7 displays the results of bond strength tests with hairline crack widths for specimens not exposed to freeze-thaw cycles, while Figure 7.2.8 shows the results of bond strength tests for specimens subjected to freeze-thaw cycles. The highest bond strength for specimens not subjected to freeze-thaw cycles was achieved with Sikadur 55 SLV, while specimens sealed with Dural 335 provided the highest bond strength for specimens subjected to freeze-thaw cycles. Specimens sealed with Duraguard 401 exposed to freeze-thaw cycles broke immediately upon removal from the freeze-thaw chamber.

Table 7.2.3 Summary of hairline crack width bond strength test results

Sealer	***Non F-T*** Bond Strength (lb)	Failure Mode*	***Non F-T*** Average Bond Strength (lb)	***F-T*** Bond Strength (lb)	Failure Mode*	***F-T*** Average Bond Strength (lb)	% Average Reduction ***(Non F-T to F-T)***
Sikadur 55SLV	8546	C	8560 (1407)**	6147	B	6020 (1162)	30%
	8665	C		5071	C,B		
	10234	C		5248	B		
	6793	C		7614	C		
Dural 335	9387	C	8329 (1751)	7789	C,B	6599 (2302)	21%
	9759	C		7933	C,B		
	8296	C		7518	C		
	5872	C		3155	C		
Sikadur 52	8717	B	7350 (1068)	3315	C,B	3845 (415)	48%
	6583	C,B		3713	B		
	6425	C		4191	C		
	7676	C		4160	C		
Degadeck Crack Sealer	5867	C	5585 (876)	3182	B	3902 (1035)	30%
	6655	C		2853	C		
	4624	C		4667	C,B		
	5192	C		4907	B		
Denedeck Crack Sealer	4870	C	5191 (504)	5795	B	4152 (2420)	20%
	5889	C		2632	B		
	5227	C		6596	C,B		
	4777	C		1586	B		
SikaPronto 19	5399	C,S	3637 (1349)	2052	B	2887 (603)	21%
	3842	B,S		3397	C,B		
	2216	S		2849	C,B		
	3092	C,S		3251	S		
Duraguard 401	2290	S	3545 (848)	0	S	0 (0)	100%
	3792	S		0	S		
	4124	S		0	S		
	3974	S		0	S		

* Failure mode: C = concrete failure, B = bond failure, S = sealant failure

** Values in parentheses show the standard deviation of the results

7.2.3.2 Narrow crack width series (1/16”)

Table 7.2.4 shows the results of the bond strength tests performed on all specimens with narrow crack widths. Sealant names shaded in gray indicate that they were also tested with hairline crack widths. The results indicate that there was a wide variation in strength among sealants tested with narrow crack widths. The bond strength ranged from an average strength of 2,291 lbs to 7,994 lbs for specimens not subjected to freeze-thaw cycles, and from 196 lbs to 5,876 lbs for those subjected to freeze-thaw cycles. Similar to specimens tested with hairline crack widths, all sealants experienced a considerable decrease in the bond strength when exposed to freeze-thaw cycles. Most sealants show a decrease in strength of about 30%, others about 60%, and one of 90%.

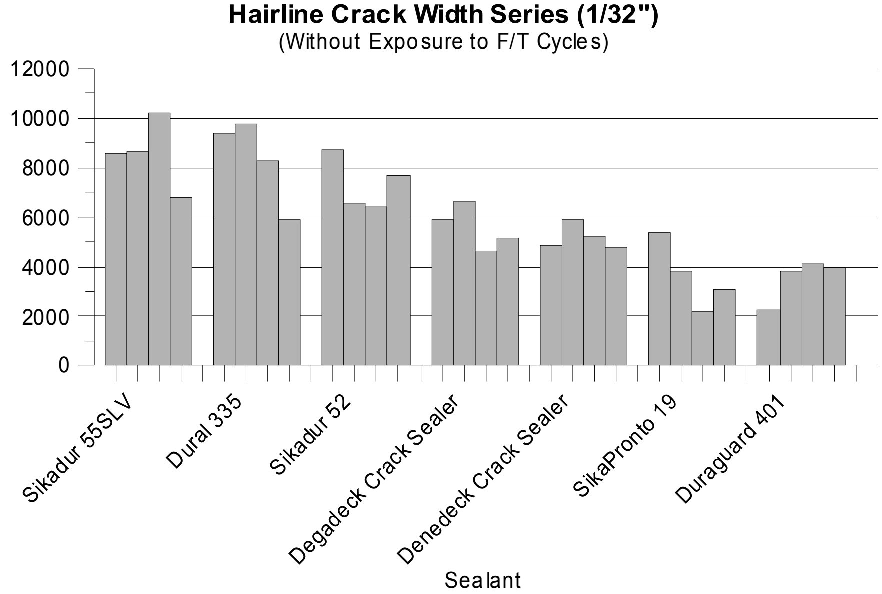


Figure 7.2.7 Bond strength of specimens not exposed to freeze-thaw cycles – hairline crack width.

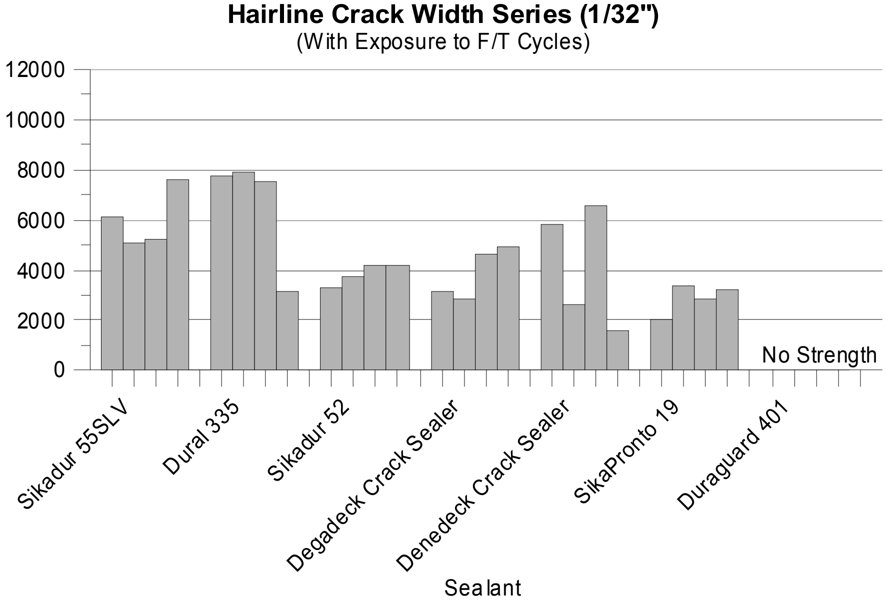


Figure 7.2.8 Bond strength of specimens exposed to freeze-thaw cycles – hairline crack width.

The results for all bond strength and durability specimens tested with narrow crack widths are shown in Figure 7.2.9 and Figure 7.2.10. Sikadur 55 SLV was found to have the highest bond strength with narrow crack widths whether it was exposed to freeze-thaw cycles or not. As before, three of the four specimens sealed with Duraguard 401 broke immediately upon removal from the freeze-thaw chamber.

Table 7.2.4 Summary of narrow crack width bond strength test results

Sealer	***Non F-T*** Bond Strength (lb)	Failure Mode*	***Non F-T*** Average Bond Strength (lb)	***F-T*** Bond Strength (lb)	Failure Mode*	***F-T*** Average Bond Strength (lb)	% Average Reduction ***(Non F-T to F-T)***
Sikadur 55SLV ***	6588	C	7994 (1148)**	5074	C	5876 (844)	27%
	8704	C		6201	C		
	9126	C,B		6913	C		
	7558	C		5316	C,B		
Sikadur 52	6716	C,B	6140 (853)	4500	C,B	4352 (1276)	29%
	5183	C,B		2549	B		
	6987	C		5530	C		
	5674	C,B		4828	C		
Degadeck Crack Sealer	5796	C	5680 (490)	4612	B	3521 (1047)	38%
	5046	C		4043	C,B		
	5648	C,B		2203	B		
	6230	C		3226	B		
Denedeck Crack Sealer	4483	C	5101 (574)	5552	B	3695 (2238)	28%
	5595	C,B		5643	B		
	5584	B		2309	B		
	4743	C		1274	B		
SikaPronto 19	3941	C,S	3552 (499)	2604	C,B	2210 (366)	38%
	3756	C,S		2388	C,B		
	2821	B,S		2085	C		
	3690	S		1763	B		
Duraguard 401	2751	S	3051 (492)	0	S	196 (392)	94%
	2540	S		783	S		
	3608	S		0	S		
	3306	S		0	S		
TK-9000	3263	C,B	2955 (537)	1060	B	1249 (335)	58%
	3161	C		1743	B		
	3245	B		1166	B		
	2152	B		1026	B		
TK-9030	2269	B	2291 (805)	1332	B	990 (295)	57%
	2583	B		873	B		
	1201	B		648	B		
	3110	B		1105	B		

* Failure mode: C = concrete failure, B = bond failure, S = sealant failure

** Values in parentheses show the standard deviation of the results

*** Sealant names shaded in gray indicate sealants that were also tested with hairline crack widths

7.2.3.3 Medium crack width series (1/8”)

Table 7.2.5 shows the results of the bond strength tests performed on specimens with medium crack widths. Sealant names shaded or hatched in gray were also tested with other crack widths. The average bond strength for specimens not exposed to freeze-thaw cycles ranged from 1,227 lbs to 6,321 lbs, and ranged from no strength to 5,572 lbs for those subjected to freeze-thaw cycles. Although all sealants experienced a reduction in bond strength when exposed to freeze-thaw cycles, the decrease in strength was more moderate for some sealants. For example, Sikadur 55 SLV and Degadeck Crack Sealer experienced only 12% reductions in strength, respectively, while the same sealants showed reductions of 30% in specimens with hairline cracks.

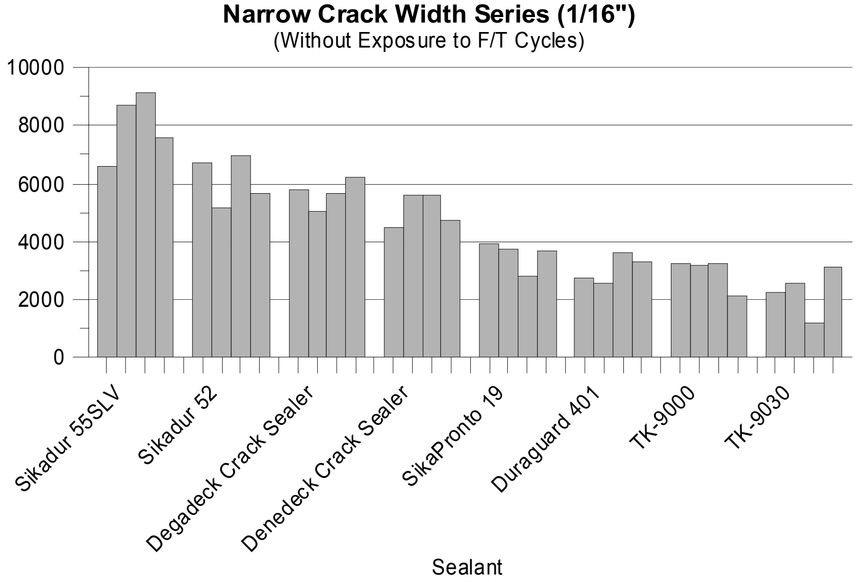


Figure 7.2.9 Bond strength of specimens not exposed to freeze-thaw cycles – narrow crack width.

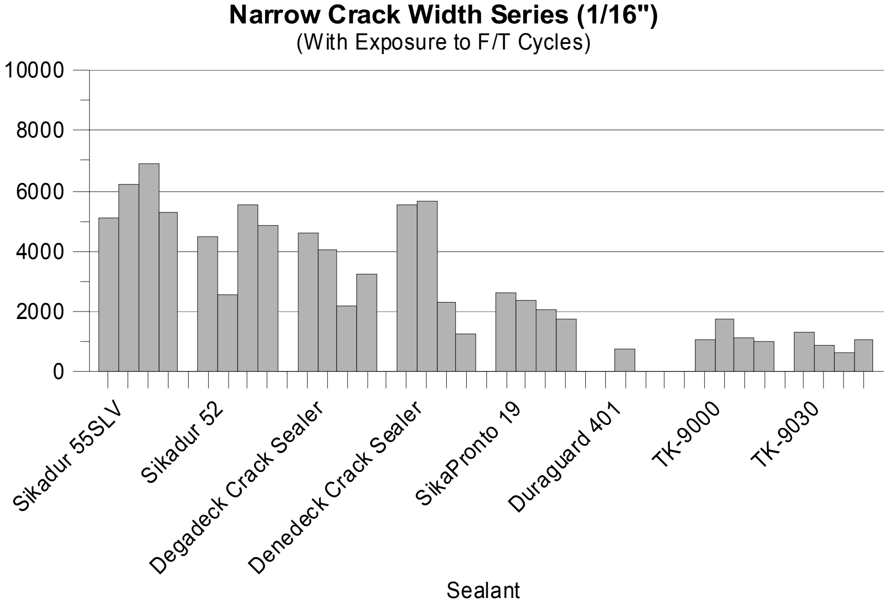


Figure 7.2.10 Bond strength of specimens exposed to freeze-thaw cycles – narrow crack width.

Similar to the narrow crack width category, Sikadur 55 SLV provided the highest bond strength among all sealants tested with medium crack widths, both for specimens exposed and not exposed to freeze-thaw cycles. A comparison of the bond strength of these specimens is shown in Figure 7.2.11 for specimens not exposed and Figure 7.2.12 for specimens exposed to freeze thaw cycles, respectivley. Again, note that all specimens sealed with Duraguard 401 subjected to freeze-thaw cycles broke immediately upon removal from the freeze-thaw chamber.

Table 7.2.5 Summary of medium crack width bond strength test results

Sealer	***Non F-T*** Bond Strength (lb)	Failure Mode*	***Non F-T*** Average Bond Strength (lb)	***F-T*** Bond Strength (lb)	Failure Mode*	***F-T*** Average Bond Strength (lb)	% Average Reduction ***(Non F-T to F-T)***
Sikadur 55SLV***	4096	C	6321 (1658)**	6388	C	5572 (1514)	12%
	7705	C		7207	C		
	7458	C		3831	B		
	6023	C		4860	C		
Sikadur 52	5991	C,B	6012 (398)	2497	B	2463 (876)	59%
	5968	C		2456	B		
	6529	C,B		1377	B		
	5558	C		3521	B		
Denedeck Crack Sealer	6019	C,B	5257 (1261)	3602	B	2498 (911)	53%
	6454	C,B		1832	B		
	4926	C,B		2884	B		
	3630	B		1675	B		
Degadeck Crack Sealer	3877	B	4129 (758)	4820	C,B	3625 (815)	12%
	4690	C,B		3380	B		
	3169	B		2985	B		
	4780	B		3315	B		
Duraguard 401	4541	S	4082 (333)	0	S	0 (0)	100%
	4010	S		0	S		
	3744	S		0	S		
	4034	S		0	S		
TK-9000	2601	B	2829 (360)	832	B	981 (224)	65%
	2887	B		776	B		
	3313	B		1049	B		
	2513	B		1267	B		
SikaPronto 19	2854	S	2772 (991)	2726	B	2249 (455)	19%
	1986	S		2047	B		
	4142	S		2509	B,S		
	2105	S		1715	C,B		
TK-9010	1110	B	1227 (273)	747	B	620 (107)	49%
	1062	B		536	B		
	1100	B		528	B		
	1635	B		670	B		

* Failure mode: C = concrete failure, B = bond failure, S = sealant failure

** Values in parentheses show the standard deviation of the results

*** Sealant names shaded in gray indicate sealants that were also tested with hairline and narrow crack widths
Sealant name hatched with stripes indicate products that were also tested with narrow crack widths

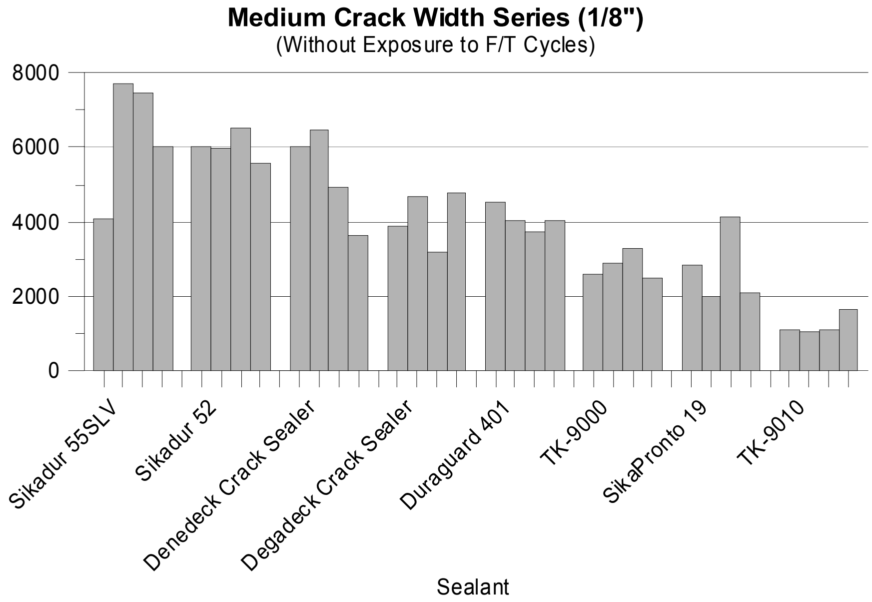


Figure 7.2.11 Bond strength of specimens not exposed to freeze-thaw cycles – medium crack width.

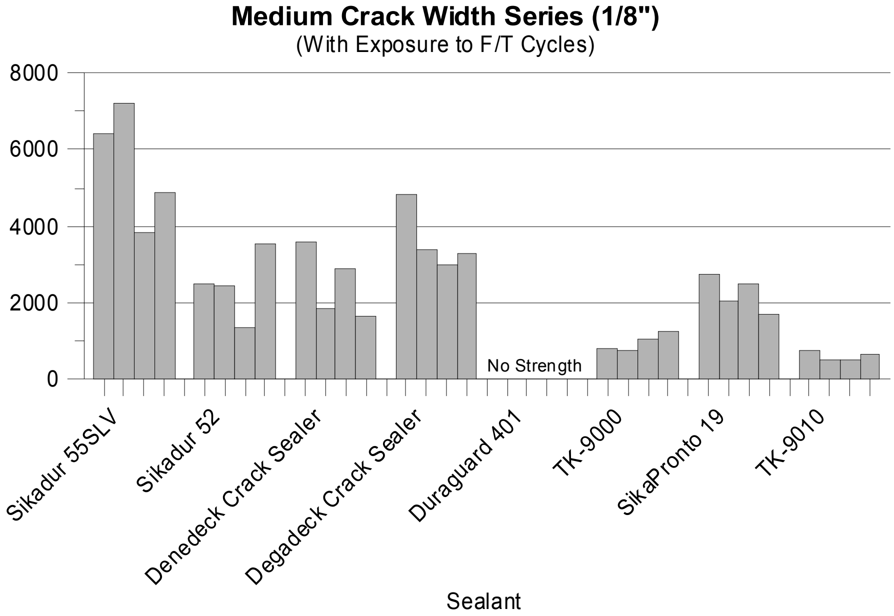


Figure 7.2.12 Bond strength of specimens exposed to freeze-thaw cycles – medium crack width.

7.2.3.4 Wide crack width series (1/5")

In this series, only two sealants, Duraguard 401 and TK 9000, could be used for wide cracks according to manufacturer specifications. Table 7.2.6 shows the results of the bond strength tests performed on specimens with these sealants. Again, both sealants experienced a considerable decrease in the bond strength when exposed to freeze-thaw cycles. Both sealants, TK 9000 and Duraguard 401 experienced reductions in bond strength of at least 50 percent. The data in Table 7.2.6 is plotted in Figures 7.2.13 and 7.2.14 for specimens not exposed and exposed to freeze-thaw cycles, respectively. Duraguard 401 provided the highest bond strength of these two sealants when not subjected to freeze-thaw cycles. However, similar to specimens tested with hairline and medium crack widths, specimens sealed with Duraguard 401 that were subjected to freeze-thaw cycles broke immediately upon removal from the freeze-thaw chamber. Therefore, TK-9000 was the only sealant (of two products) tested in this study with wide crack widths that could endure freeze-thaw cycles.

Table 7.2.5 Summary of wide crack width bond strength test results

Sealer	***Non F-T*** Bond Strength (lb)	Failure Mode*	***Non F-T*** Average Bond Strength (lb)	***F-T*** Bond Strength (lb)	Failure Mode*	***F-T*** Average Bond Strength (lb)	% Average Reduction ***(Non F-T to F-T)***
Duraguard 401	3511	S	3409 (430)	0	S	0 (0)	100%
	3819	S		0	S		
	2803	S		0	S		
	3503	S		0	S		
TK-9000	2931	B	1938 (675)	712	B	882 (239)	55%
	1780	B		1186	B		
	1562	B		673	B		
	1477	B		958	B		

* Failure mode: C = concrete failure, B = bond failure, S = sealant failure

** Values in parentheses show the standard deviation of the results

*** Sealant name shaded in gray was also tested with hairline, narrow, and medium crack widths
Sealant name hatched with diagonal stripes was also tested with narrow and medium crack widths

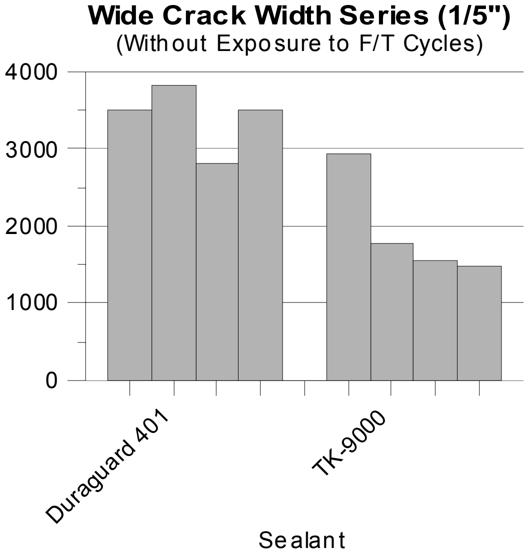


Figure 7.2.13 Bond strength of specimens not exposed to freeze-thaw cycles – wide crack width.

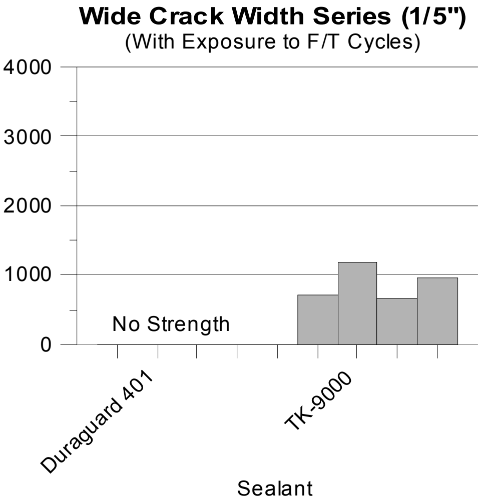


Figure 7.2.14 Bond strength of specimens exposed to freeze-thaw cycles – wide crack width.

7.3 Discussion of Test Results

7.3.1 Failure mode

7.3.1.1 Variation within a given crack width

In the following, the trends observed only in specimens with hairline cracks are discussed because specimens with larger crack widths showed similar trends. However, any trends specific to a particular crack width are noted.

Several failure modes were observed during the bond strength tests of specimens with hairline crack widths as shown previously in Table 7.2.3. For specimens not exposed to freeze-thaw cycles, the specimens with the highest average bond strengths displayed primarily concrete failures. The sealant with the lowest average bond strength, Duraguard 401, exhibited only sealant failures. SikaPronto 19, however, displayed a combination of sealant, concrete and bond failures.

The variation in bond strength among the sealants exhibiting concrete failures was significant (see Table 7.2.3), considering that the strength of these specimens was limited by the strength of the concrete. The sealants with the highest bond strengths (8,560 lbs, 8,329 lbs, and 7,350 lbs) were cast from batches nine and ten with average compressive strengths of 6,713 and 6,710 psi, respectively. On the other hand, the sealants with the lowest bond strengths (5,585 lbs and 5,191 lbs) were cast from batches five and six with average compressive strengths of 6,220 and 6,207 psi, respectively. Although these last two specimens did have lower compressive strengths, the variation in bond strength from these two groups of sealants cannot be attributed to differences in concrete strength alone (see section 7.2.1).

In general, sealants which displayed primarily concrete failures had the highest bond strengths, followed by a combination of concrete and bond failures. Bond failures were generally associated with lower bond strengths. The lowest bond strengths were generally associated with sealant failures. Concrete failures are desirable because it means that the sealant adhered well to the crack faces and was strong enough to induce failure of the concrete rather than of the sealant. Thus, sealants which exhibit primarily concrete failures regardless of the crack width can be considered to provide adequate bond strength. The sealants that exhibited primarily concrete failures and provided the best performance with hairline cracks in this test program are the following: Sikadur 55 SLV, Dural 335, Sikadur 52, Degadeck Crack Sealer, and Denedeck Crack Sealer.

7.3.1.2 Influence of crack width

Table 7.3.1 displays the average bond strength and failure mode for specimens with hairline, narrow, medium and wide crack widths not subjected to freeze-thaw cycles. It may be observed that nearly all specimens exhibited concrete failures among the strongest sealants tested with hairline crack widths (Sikadur 55 SLV, Dural 335, Sikadur 52, Degadeck Crack Sealer, and Denedeck Crack Sealer). As the crack width increased, however, concrete failures became less common, and became a combination of concrete and bond failures. As the amount of sealant is increased within a specimen (i.e., as the crack width is increased), the area enclosing the crack and sealant becomes weaker in comparison with the surrounding concrete, because the amount of sealant is large enough to significantly impact the strength and stiffness of the cross section. As a result, a larger number of bond and/or sealant failures can be expected occur with increasing crack width.

An example of this trend is given by SikaPronto 19, which displayed combinations of concrete, bond and sealant failures with hairline crack widths, but transitioned to exclusively sealant failures when tested with medium crack widths. Another example is Degadeck which exhibited only concrete failures with hairline cracks, and then transitioned to almost exclusively bond failures when tested with medium crack widths.

Table 7.3.1 Average bond strength and failure modes observed for each sealant not exposed to freeze-thaw cycles.

		Hairline		Narrow		Medium		Wide	
	Sealer	Failure Mode*	Ave. Bond Strength (lb)	Failure Mode*	Ave. Bond Strength (lb)	Failure Mode*	Ave. Bond Strength (lb)	Failure Mode*	Ave. Bond Strength (lb)
1	Sikadur 55 SLV	C	8560	C	7994	C	6321		
		C		C		C			
		C		C,B		C			
		C		C		C			
2	Dural 335	C	8329						
		C							
		C							
		C							
3	Sikadur 52	B	7350	C,B	6140	C,B	6012		
		C,B		C,B		C			
		C		C		C,B			
		C		C,B		C			
4	Degadeck Crack Sealer	C	5585	C	5680	B	4129		
		C		C		C,B			
		C		C,B		B			
		C		C		B			
5	Denedeck Crack Sealer	C	5191	C	5101	C,B	5257		
		C		C,B		C,B			
		C		B		C,B			
		C		C		B			
6	SikaPronto 19	C,S	3637	C,S	3552	S	2772		
		B,S		C,S		S			
		S		B,S		S			
		C,S		S		S			
7	Duraguard 401	S	3545	S	3051	S	4082	S	3409
		S		S		S		S	
		S		S		S		S	
		S		S		S		S	
8	TK-9000			C,B	2955	B	2829	B	1938
				C		B		B	
				B		B		B	
				B		B		B	
9	TK-9010					B	1227		
						B			
						B			
						B			
10	TK-9030			B	2291				
				B					
				B					
				B					

* Failure mode: C = concrete failure, B = bond failure, S = sealant failure

The first five sealants listed in Table 7.3.1 (shown above the thick black line) exhibited much larger bond strengths than the rest of them with hairline, narrow and medium crack widths. The average bond strength of these sealants always exceeded the average bond strength of the other sealants, irrespective of the crack width. Furthermore, the last five sealants listed in the table displayed primarily bond or sealant failures, which suggest that the strength of the sealant was the main contributing factor limiting bond strength.

The performance of the specimens tested with wide crack widths was limited by the sealant. Although sealants one through five in Table 7.3.1 are not recommended for wide crack widths by the manufacturer, the test results with smaller crack widths suggest that they could also be used for wide crack widths and still perform well. Furthermore, the strengths obtained for the narrow and medium crack widths suggest that they could provide as much or more strength than the sealants recommended for wide cracks by their manufacturers (i.e., Duraguard 401 and TK 9000).

7.3.2 Effect of freeze-thaw cycles

Figure 7.3.1 shows a graphical summary of all bond strength test result averages for sealants tested with each crack width. As was expected, all sealants experienced a reduction in bond strength when subjected to freeze-thaw cycles, but the reduction in strength varied for each sealant and each crack width as described previously. Sikadur 55 SLV provided the highest average bond strength among those exposed and not exposed to freeze-thaw cycles for sealants tested with narrow and medium crack widths. It also exhibited the smallest reduction in bond strength among all sealants when tested with medium cracks. Duraguard 401 experienced 100% reduction in bond strength for specimens with hairline, medium and wide crack widths when exposed to freeze-thaw cycles, as the specimens broke immediately after removal from the freeze-thaw chamber.

As noted earlier, the reduction in strength when exposed to freeze-thaw cycles varied for each sealant and each crack width. For example, Sikadur 52 experienced only a moderate (29%) reduction in strength when tested with narrow cracks, but suffered considerably larger reductions in strength with hairline (48%) and medium (59%) crack widths. This example illustrates that sealants can perform well in a range of crack widths when not exposed to freeze-thaw cycles, but they can suffer severe reductions in strength at certain crack widths when exposed to freeze-thaw cycles.

Table 7.3.2 shows a summary of the average bond strength and failure modes for all sealants and crack widths in specimens exposed and not exposed to freeze-thaw cycles. The data show that Sikadur 55 SLV experienced a decrease in bond strength with increasing

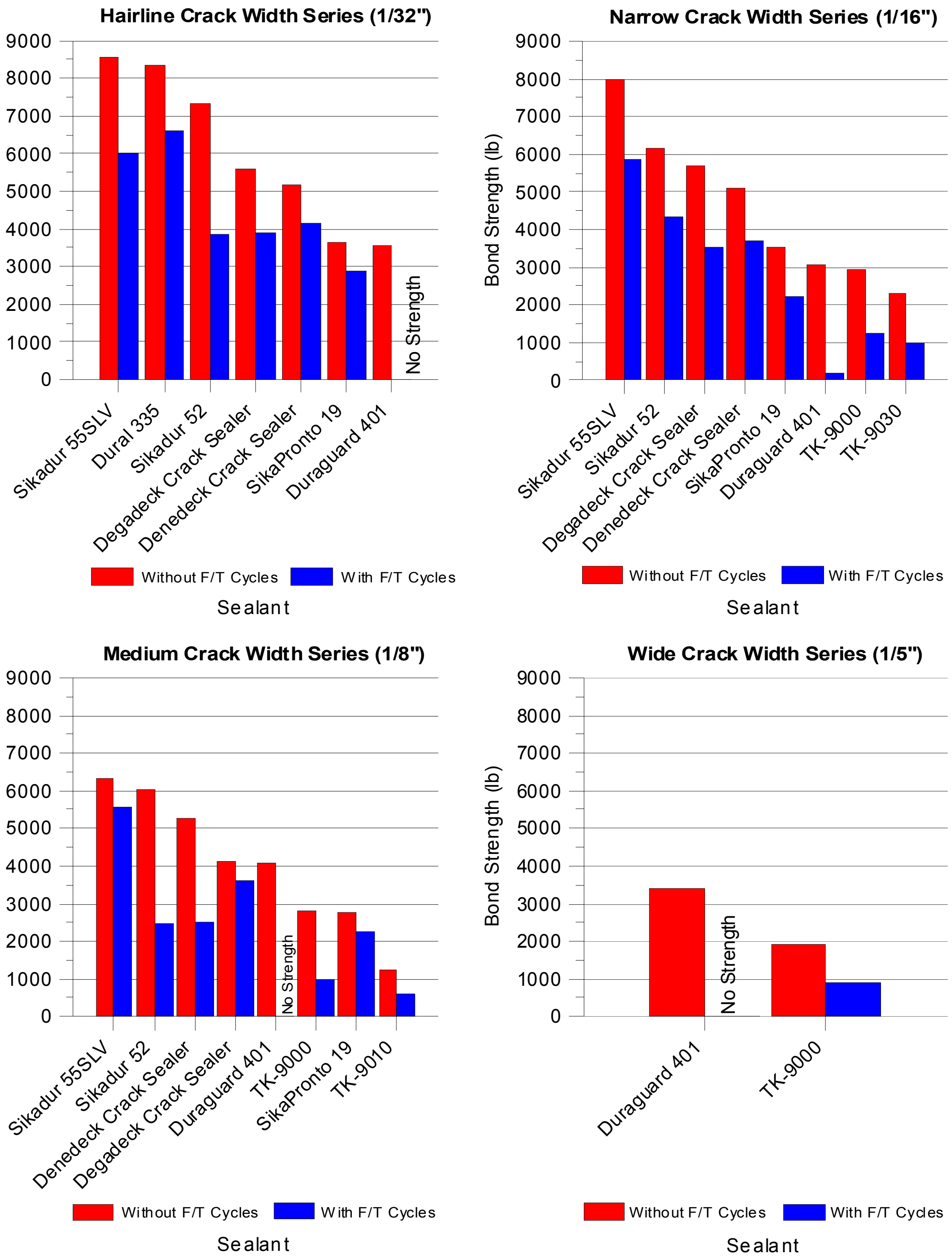


Figure 7.3.1 Summary of bond strength test results for each sealant tested with each crack width.

Table 7.3.2 Average bond strength and failure modes observed for each sealant, with and without exposure to freeze-thaw cycles

		Hairline Crack Width Series				Narrow Crack Width Series				Medium Crack Width Series				Wide Crack Width Series			
		Without F/T Cycles		With F/T Cycles		Without F/T Cycles		With F/T Cycles		Without F/T Cycles		With F/T Cycles		Without F/T Cycles		With F/T Cycles	
	Sealer	Failure Mode*	Average Bond Strength (lb)	Failure Mode*	Average Bond Strength (lb)	Failure Mode*	Average Bond Strength (lb)	Failure Mode*	Average Bond Strength (lb)	Failure Mode*	Average Bond Strength (lb)	Failure Mode*	Average Bond Strength (lb)	Failure Mode*	Average Bond Strength (lb)	Failure Mode*	Average Bond Strength (lb)
1	Sikadur 55 SLV	C	8560	B	6020	C	7994	C	5876	C	6321	C	5572				
		C		C,B		C		C		C		C					
		C		B		C,B		C		C		B					
		C		C		C		C,B		C		C					
2	Dural 335	C	8329	C,B	6599												
		C		C,B													
		C		C													
		C		C													
3	Sikadur 52	B	7350	C,B	3845	C,B	6140	C,B	4352	C,B	6012	B	2463				
		C,B		B		C,B		B		C		B					
		C		C		C		C		C,B		B					
		C		C		C,B		C		C		B					
4	Degadeck Crack Sealer	C	5585	B	3902	C	5680	B	3521	B	4129	C,B	3625				
		C		C		C		C,B		C,B		B					
		C		C,B		C,B		B		B		B					
		C		B		C		B		B		B					
5	Denedeck Crack Sealer	C	5191	B	4152	C	5101	B	3695	C,B	5257	B	2498				
		C		B		C,B		B		C,B		B					
		C		C,B		B		B		C,B		B					
		C		B		C		B		B		B					

Table 7.3.2 Average bond strength and failure modes observed for each sealant, with and without exposure to freeze-thaw cycles (Continued)

		Hairline Crack Width Series				Narrow Crack Width Series				Medium Crack Width Series				Wide Crack Width Series			
		Without F/T Cycles		With F/T Cycles		Without F/T Cycles		With F/T Cycles		Without F/T Cycles		With F/T Cycles		Without F/T Cycles		With F/T Cycles	
	Sealer	Failure Mode*	Average Bond Strength (lb)	Failure Mode*	Average Bond Strength (lb)	Failure Mode*	Average Bond Strength (lb)	Failure Mode*	Average Bond Strength (lb)	Failure Mode*	Average Bond Strength (lb)	Failure Mode*	Average Bond Strength (lb)	Failure Mode*	Average Bond Strength (lb)	Failure Mode*	Average Bond Strength (lb)
6	SikaPronto 19	C,S	3637	B	2887	C,S	3552	C,B	2210	S	2772	B	2249				
		B,S		C,B		C,S		C,B		S		B					
		S		C,B		B,S		C		S		B,S					
		C,S		S		S		B		S		C,B					
7	Duraguard 401	S	3545	S	0	S	3051	S	196	S	4082	S	0	S	3409	S	0
		S		S		S		S		S		S		S		S	
		S		S		S		S		S		S		S		S	
		S		S		S		S		S		S		S		S	
8	TK-9000					C,B	2955	B	1249	B	2829	B	981	B	1938	B	882
						C		B		B		B		B		B	
						B		B		B		B		B		B	
						B		B		B		B		B		B	
9	TK-9010									B	1227	B	620				
										B		B					
										B		B					
										B		B					
10	TK-9030					B	2291	B	990								
						B		B									
						B		B									
						B		B									

* Failure mode: C = concrete failure, B = bond failure, S = sealant failure

crack width, and a decrease in the bond strength for a given crack width when exposed to freeze-thaw cycles. The failure mode for specimens sealed with Sikadur 55 SLV, however, remained essentially unchanged, displaying concrete failures regardless of the crack width and exposure to freeze-thaw cycles. Therefore, it may be concluded that the decrease in bond strength under freeze-thaw cycles is due to deterioration of the *concrete* and not necessarily due to a decline in the strength or performance of this sealant. Overall, Sikadur 55 SLV displayed excellent performance for each crack width for which it was tested, even when exposed to freeze-thaw cycles.

Sealants three through five in Table 7.3.2 transitioned from combinations of concrete and bond failures to nearly exclusively bond failures when exposed to freeze-thaw cycles, especially for larger crack widths. These sealants all experienced reductions in average bond strength when exposed to freeze-thaw cycles. It cannot be determined with certainty, however, whether the reduction in bond strength of these specimens resulted from a degradation of the sealant or the concrete, or both, since the quality of each contributes to a good adherence of the sealant to the concrete.

Sealants with lower strengths tended to exhibit the same failure mode with and without exposure to freeze-thaw cycles, and irrespective of the crack width. Sealants eight through ten in Table 7.3.2 exhibited almost exclusively bond failures, whether they were exposed to freeze-thaw cycles or not. They also experienced a reduction in strength when exposed to freeze-thaw cycles.

Sealant seven (Duraguard 401) was tested with each of the four crack widths. All specimens exhibited sealant failures. When exposed to freeze-thaw cycles, however, Duraguard 401 was damaged enough that specimens tested with three of the four crack widths had no strength, but still exhibited sealant failures when they broke upon removal from the freeze-thaw chamber. Thus, while other sealants experienced only moderate reductions in strength that could have been due to a degradation of the sealant or the concrete when exposed to freeze-thaw cycles, the performance of Duraguard 401 itself was severely affected by freeze-thaw cycles.

7.3.3 Bond Strength

In this section, the strength of concrete joints is compared to the measured bond strength of the specimens with crack sealants. The purpose of this comparison is simply to provide a benchmark for the measured strength of the sealants. Past experimental studies on unreinforced concrete construction joints have shown that the strength of a concrete joint can be approximately estimated as (6 to 8) $\sqrt{f_c`}$, regardless of the joint surface preparation (Hanson, 1960; Paulay et al., 1974; Djazmati et al., 2000). Here, the shear stress for crack sealant specimens used in this test program is defined as the measured peak load applied divided by the sealant (bond) area, 2.5 in. by 4 in. The result can be normalized with respect to $\sqrt{f_c`}$, and averaged for all specimens with a given sealant tested with a given crack width.

In Figure 7.3.2, the average shear stress normalized with respect to $\sqrt{f_c`}$ is shown for all sealants not exposed to freeze-thaw cycles. Specimens exposed to freeze-thaw cycles were not included, since the compressive strength of the concrete after exposure to freeze-thaw cycles was not measured.

With hairline crack widths, five sealants showed bond strengths that exceeded a value of $6\sqrt{f_c`}$, (i.e., the lower bound for concrete joints). These sealants are: Sikadur 55 SLV, Dural 335, Sikadur 52, Degadeck Crack Sealer and Denedeck Crack Sealer. In other words, these sealants were able not only to seal the crack, but also to permit the development of a strength comparable to that of a concrete joint.

For narrow and medium crack widths, the same sealants showed similar performance, except that Degadeck Crack Sealer no longer provided a strength of at least $6\sqrt{f_c`}$ for medium cracks. It should be noted that the four sealants in narrow crack widths that exceeded the benchmark criterion, were the same sealants which showed good performance based on the previous discussion of failure modes and average bond strength in section 7.3.1.

Figure 7.3.2 also shows that neither of the two sealants tested with wide crack widths met the benchmark. Again, this result agrees with the observations made in section 7.3.1.2, as the bond strength of specimens sealed with Duraguard 401 and TK-9000 was low and limited by the performance of the sealant.

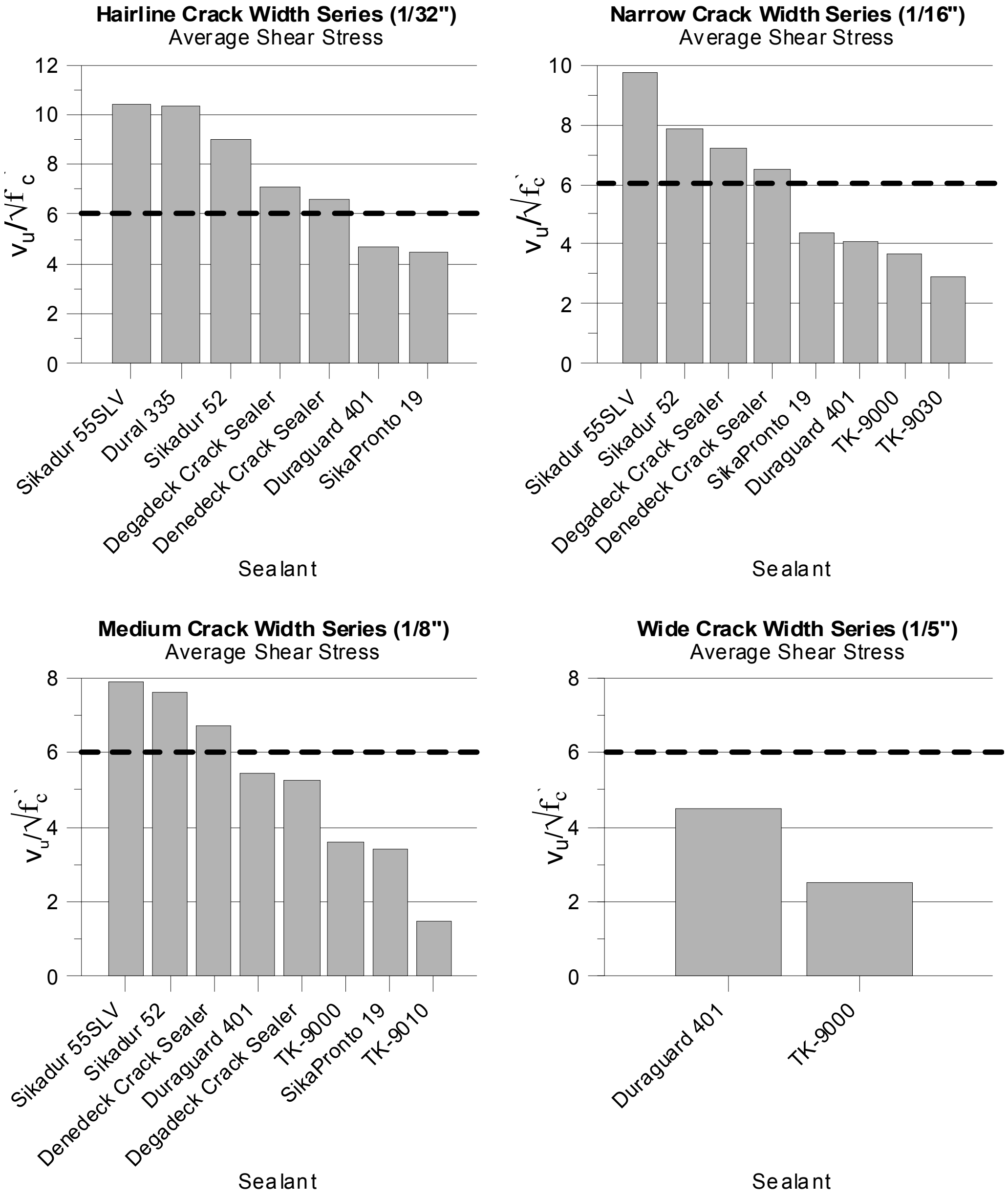


Figure 7.3.2 Average shear stress normalized with respect to $\sqrt{f_c}$` for all sealants tested with each crack width.

7.3.4 Sealant performance evaluation

In section 3.3.1, a preliminary evaluation was done to review and rank the crack sealants according to the product characteristics. The potential products were identified and and a composite score was computed for each product based on their most desirable qualities (see Table 3.3.3).

Based on the results and discussion presented in the previous sections, a summary of crack sealant performance is presented in Table 7.3.3. The number in parentheses after the sealant name indicates the rank of the product based on the composite score computed in Table 3.3.3. Similar to the approach used to rank the deck sealants, crack sealants with comparable performance were assigned to a performance group category, I, II, or III for the best, moderate, or lowest performance, respectively.

Table 7.3.3 Summary of crack sealant performance

Hairline Crack Width (< 0.06 in.)	**Narrow Crack Width** (0.06 - 0.10 in.)	**Medium Crack Width** (0.10 - 0.19 in.)	**Wide Crack Width** (> 0.20 in.)	**Performance Group Category**
Sikadur 55 SLV (4)*	Sikadur 55 SLV (4)	Sikadur 55 SLV (4)	No products tested	I
Dural 335 (5)				
Sikadur 52 (6)	Sikadur 52 (6)	Sikadur 52 (7)	No products tested	II
Degadeck Crack Sealer (1)	Degadeck Crack Sealer (1)	Degadeck Crack Sealer (1)		
Denedeck Crack Sealer (2)	Denedeck Crack Sealer (2)	Denedeck Crack Sealer (2)		
SikaPronto 19 (7)	SikaPronto 19 (8)	SikaPronto 19 (8)	Duraguard 401 (1)	III
Duraguard 401 (3)	Duraguard 401 (3)	Duraguard 401 (3)	TK 9000 (2)	
	TK 9000 (6)	TK 9000 (6)		
	TK 9030 (5)	TK 9010 (5)		

* The number in parentheses indicates the product rank based on the composite score computed in section 3.3.1

7.3.4.1 Hairline Crack Widths

Among the products for use in hairline cracks, Sikadur 55 SLV and Dural 335 offered the best performance and were assigned to Performance Group Category I. They exhibited the largest bond strength and mostly concrete failures, and had relatively low strength loss after exposure to freeze-thaw cycles. Sealants assigned to Performance Group Category II are Sikadur 52, Degadeck Crack Sealer and Denedeck Crack Sealer. These sealants also exhibited good performance, but they showed larger reductions in bond strength after exposure to freeze-thaw cycles. It should be noted, however, that Degadeck Crack Sealer and Denedeck Crack Sealer were ranked higher than Sikadur 55 SLV and Dural 335 based on the preliminary product evaluations (see Table 7.3.3). This was mainly due to the increased time to open to traffic of Sikadur 55 SLV (6 hrs) and Dural 335 (4 – 6 hours) compared to that of Degadeck Crack Sealer (35 – 45 minutes) and Denedeck Crack Sealer (45 min. – 1 hour). These last two sealants offer much shorter times to open to traffic and may be able to provide adequate strength and durability for short term needs. Situations like the one just mentioned demonstrate that it is important to consider all product characteristics and the specific needs of the project in which a sealant will be used.

SikaPronto 19 and Duraguard 401 had significantly lower strengths than sealants in Performance Group Categories I and II, they displayed high proportions of bond or sealant failures, and had significant reductions in strength after exposure to freeze-thaw cycles. Duraguard 401 had no strength after exposure to freeze-thaw cycles. As a result, these products were assigned to Performance Category III.

7.3.4.2 Narrow and Medium Crack Widths

Only one product (Sikadur 55 SLV) was assigned to Performance Group Category I in this crack range. This sealant showed mainly concrete failures and low strength loss after exposure to freeze-thaw cycles. Sikadur 52, Degadeck Crack Sealer, and Denedeck Crack Sealer were assigned to Performance Group Category II. These three sealants provided lower bond strengths than Sikadur 55 SLV with and without exposure to freeze-thaw cycles, but provided higher strengths than the other sealants studied. Again, Degadeck Crack Sealer and Denedeck Crack Sealer may be attractive choices for decks scheduled for overlays or replacement, as the decrease in performance due to freeze-thaw cycles will not be as important if they are intended to provide protection for only a short period.

SikaPronto 19, Duraguard 401, TK 9000, TK 9010, and TK 9030 were assigned to Performance Group Category III. These sealants had much lower bond strengths, and displayed almost exclusively bond or sealant failures.

7.3.4.3 Wide Crack Widths

There were no products assigned to Performance Group Category I or II in this crack width range. The two sealants tested with wide crack widths were both assigned to Performance Group Category III. Duraguard exhibited sealant failures with relatively low strengths, and experienced a complete loss of strength after exposure to freeze-thaw cycles. TK 9000 displayed exclusively bond failures and had very low bond strength before and after exposure to freeze-thaw cycles.

While Duraguard 401 and TK 9000 were the only two products recommended by the manufacturer for sealing wide cracks, it is possible that other sealants that exhibited good performance with narrower cracks could provide sufficient strength if used to seal wide cracks. The test data obtained in this study suggest, for example, that Sikadur 55 SLV (which displayed exceptional performance with hairline, narrow and medium cracks) could also be used for wide cracks. Additional tests should, however, be performed to corroborate this hypothesis.

Chapter 8

Summary and Conclusions

8.1 Summary

Deck and crack sealants are commonly used in bridge decks in order to deter chloride ion intrusion into the concrete. Although deck and crack sealants have been used for some time in Wisconsin and in other states, little is known about their performance over time. Additionally, the effectiveness of sealants exposed to freezing and thawing cycles normally encountered in Wisconsin is unknown.

The primary objective of this study was to conduct a systematic assessment of the effectiveness and relative performance of concrete bridge deck and crack sealants. A total of thirteen deck sealants and ten crack sealants were selected for study in consultation with the Project Oversight Committee. Feedback from District Bridge Maintenance Engineers, a general literature review of deck and crack sealant products, and a list of WisDOT approved products were used to select sealants for laboratory study. In addition, the characteristics of the selected products were evaluated and ranked in a variety of categories including, surface preparation requirements, environmental application conditions, expected durability, time to open traffic, and coverage rate and cost.

The study on deck sealants was divided into two components. In the first component, sealant performance was assessed by measuring its resistance to chloride ion intrusion. The concrete specimens used throughout this test program were cast from the Grade D concrete mix design as designated in the Wisconsin Bridge Manual. Concrete specimens were sealed, sandblasted and ponded with a sodium chloride solution for 90 days in accordance with the provisions of AASHTO T 259. Additional specimens were subjected to freeze-thaw cycles while being ponded to simulate the deterioration of the sealants over time in a severe environment. After ponding, specimens were allowed to dry, and samples were removed and tested for the chloride ion content in accordance with AASHTO T 260.

In the second component of this study, the penetration depth profile below the sealed surface was measured using a dye method. Although this test is not required under the current AASHTO standards, it was included in this study in an attempt to establish a relationship between penetration depth and resistance to chloride ion intrusion. The concrete specimens used in these tests were sealed, but not sandblasted. Specimens were immersed in a dye-water solution, which outlined the sealant depth of penetration profile and allowed it to be measured.

The study on crack sealants was also divided into two components. In the first component, sealant performance was assessed by measuring the ability of the sealants to penetrate and fill cracks. Concrete specimens with prescribed crack widths were prepared and sealed according to the manufacturers' specifications. The specimens were saw-cut through the thickness at two locations. The depth of penetration of the sealant was observed and measured, as well as the sealant's ability to partially or completely fill the crack.

In the second component, the bond strength of the crack sealants was measured using a test procedure similar to that used to obtain the splitting tensile strength of concrete. The durability of the crack sealants was measured using additional specimens subjected to freeze-thaw cycles before measuring their bond strength.

Based on the laboratory test data, the performance of the sealants was compared and ranked. Sealants with comparable performance were assigned to a performance group category defined as follows. Those with the best performance were assigned to group category I. Sealants with moderate performance were assigned to category II, while the sealants with the lowest performance were assigned to group category III. The results of this study also showed that the test procedures could be modified for reducing data scatter and for a better assessment of the products. Recommendations for modifying the current test methods and field testing are provided.

8.2 Main Findings

8.2.1 Deck sealants

a) On average, solvent-based, silane products had larger depths of penetration than water-based or siloxane products. The depth of penetration of solvent-based products ranged between 1.8 mm and 3.8 mm. In contrast, water-based products had penetration depths ranging from 1.4 mm to 2.1 mm.

b) When not exposed to freeze-thaw cycles, solvent-based products were generally able to reduce the ingress of chloride ions better than water-based products. Under exposure to freeze-thaw cycles, however, there was no clear distinction between the performance of solvent- and water-based.
c) None of the thirteen deck sealants included in this study reached the penetration depths suggested by the manufacturer.
d) Only one sealant, Hydrozo Silane 40 VOC, was able to penetrate beyond the target sandblasting depth required by the AASHTO T 259 standard, 3.2 mm.
e) Exposure to freeze-thaw cycles decreased the ability of most sealants to reduce chloride ion ingress, shown by an increase in the ratio of absorbed. However, a few products (Sonneborn Penetrating Sealer 40 VOC, V-Seal, Aqua-Trete BSM 20 and Hydrozo Enviroseal 20) were essentially unaffected by exposure to freeze-thaw cycles.
f) The sealants' depth of penetration profile and the chloride ion content measured at different locations on a given specimen showed considerable scatter. Standard deviations for the depth of penetration measurements ranged from 48 to 83 percent of the average, while standard deviations for the measured chloride ion content ranged from 15 to 90 percent of the average.

8.2.2 Crack sealants

a) All sealants studied were able to penetrate the full depth of the crack designed for this study, 2.5 inches, irrespective of the crack width considered.
b) For most sealants, the bond strength decreased, and the failure mode changed with increasing crack width, and with exposure to freeze-thaw cycles.
c) Reductions in bond strength under freeze-thaw cycles varied widely depending on the product and the crack width considered.
d) Sealants which were tested for different crack widths tended to exhibit similar performance in each crack width, i.e., crack width did not appear to have a significant influence on the performance of the sealant.

8.3 Conclusions

8.3.1 Deck sealants

a) When not exposed to freeze-thaw cycles, three sealants, Hydrozo Silane 40 VOC, Sonneborn Penetrating Sealer 40 VOC and Aquanil Plus 40 would be accepted according to the current WisDOT acceptance criteria.

b) On the basis of the laboratory tests conducted in this study, and a relative comparison of all the sealants with and without exposure to freeze-thaw cycles, Hydrozo Silane 40 VOC and Sonneborn Penetrating Sealer 40 VOC, exhibited consistently good performance throughout all the tests and offered the best protection against chloride ion intrusion.

c) Several sealants (Powerseal 40%, V-Seal, Penseal 244, TK 290-WDOT, Hydrozo Enviroseal 40 and Aqua-Trete BSM 20) were able to offer moderate protection to the concrete, but were adversely affected by exposure to freeze-thaw cycles.

d) The large abrasion depth required by AASHTO T 259 was the key factor limiting the effectiveness of the sealants with shallower depths of penetration. Some of these sealants could perform well in the field depending on the actual amount of abrasion and/or frequency of resealing.

e) Because of their shallow depths of penetration, TK 290-WB, Hydrozo Enviroseal 20, Baracade WB 244, Eucoguard 100, were the least effective products under freeze-thaw cycles. Aquanil Plus 40, was effective without exposure to freeze-thaw cycles, but it performance decreased sharply under freeze-thaw cycles.

f) The performance of deck sealant products must be evaluated under freeze-thaw cycles. Many sealants were able to provide good or moderate protection to the concrete when not exposed to freeze-thaw cycles, but their performance severely declined when exposed to freeze-thaw cycles.

8.3.2 Crack sealants

a) Among the products for use in hairline cracks, Sikadur 55 SLV and Dural 335, exhibited the best performance in the bond strength and durability tests. Other sealants that performed well for sealing hairline cracks include: Sikadur 52, Degadeck Crack Sealer and Denedeck Crack Sealer. SikaPronto 19 and Duraguard 401, however, had low bond strength and/or showed large reductions in strength when exposed to freeze-thaw cycles.

b) In the narrow and medium crack width range, Sikadur 55 SLV was the most effective product. Sikadur 52, Degadeck Crack Sealer, and Denedeck Crack Sealer performed well when not exposed to freeze-thaw cycles, but their performance deteriorated considerably under freeze-thaw cycles. SikaPronto 19, Duraguard 401, TK 9000, TK 9010 and TK 9030, on the hand, were the least effective products in this crack width range.

c) The two sealants studied for use in wide cracks (TK 9000 and Duraguard 401) performed poorly in comparison with the rest of the sealants included in this study. Their bond strength was significantly lower and it was significantly affected by freeze-thaw cycles.

d) Exposure to freeze-thaw cycles was detrimental to the performance of the majority of the crack sealants studied. Therefore, future evaluation of crack sealants must include specimens subjected to freeze-thaw cycles.

8.4 Recommendations for Future Testing

a) The depth of penetration test outlined in this report could be used as a rapid, effective tool for screening deck sealants prior to conducting the more time consuming chloride ion intrusion tests. Products with very shallow depths of penetration should, perhaps, not be considered unless they could be used on decks expected to have low abrasion or as short term solutions.

b) Future studies on deck and crack sealants should include evaluation of the performance of the products under freeze-thaw cycles. The results of this study showed that products which were effective at deterring chloride ion intrusion without exposure to freeze-thaw cycles, will not necessarily perform well when exposed to freeze-thaw cycles.

c) The results from the chloride ion analysis tests showed large scatter. Future chloride ion analysis tests should consider sampling and testing at more locations over each block to reduce the scatter in the data. This will increase the time/cost of the tests somewhat, but will improve the reliability of the results without the need for fabricating and long-term ponding of additional specimens.

d) Bond strength and durability tests on Sikadur 55 SLV in wide cracks are recommended. This crack sealant is not intended to be used for wide cracks according to the manufacturer, but its good performance in hairline, narrow and medium cracks suggests that it could also do well and be used for wide cracks.

e) Field tests should be performed on recently sealed bridge decks to monitor the performance of the products using, for example, core samples to evaluate the penetration of the sealants. Chloride ion analysis tests could be performed at designated intervals, and the results used to decide when or if decks need to be resealed. Also, a comprehensive field performance evaluation should be developed to help monitor and make decisions about deck and crack sealant use. For example, the sealants found to be most effective in this study could be applied to selected bridge decks in order to monitor their long-term performance under actual field conditions.

References

Aitken, C., and Litvan, G., "Laboratory Investigation of Concrete Sealers," *Concrete International,* Vol. 11, Issue 11, November, 1989, pp. 37-42.

American Association of State Highway and Transportation Officials (AASHTO), *Standard Method of Test for Making and Curing Concrete Test Specimens in the Laboratory,* AASHTO Designation T 126-01, Washington, D.C., 2004.

American Society of Testing and Materials (ASTM), *Making and Curing Concrete Test Specimens in the Laboratory,* ASTM Designation C 192-95, West Conshohocken, Pennsylvania, 2004.

American Association of State Highway and Transportation Officials (AASHTO), *Standard Method of Test for Resistance of Concrete to Chloride Penetration,* AASHTO Designation T 259-02, Washington, D.C., 2004.

American Association of State Highway and Transportation Officials (AASHTO), *Standard Test Method for Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials,* AASHTO Designation T 260-02, Washington, D.C., 2004.

American Society of Testing and Materials (ASTM), *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens,* ASTM Designation C 496-96, West Conshohocken, Pennsylvania, 2004.

American Society of Testing and Materials (ASTM), *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing,* ASTM Designation C 666-97, West Conshohocken, Pennsylvania, 2004.

American Society of Testing and Materials (ASTM), *Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals,* ASTM Designation C 672-03, West Conshohocken, Pennsylvania, 2004.

American Society of Testing and Materials (ASTM), *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration,* ASTM Designation C 1202-97, West Conshohocken, Pennsylvania, 2004.

Berman, H.A., "Determination of Chloride in Hardened Portland Cement Paste, Mortar, and Concrete," *FHWA-RD-72-12*, Federal Highway Administration, Washington, D.C., September, 1972.

Bradbury, A., and Chojnacki, B., "A Laboratory Evaluation of Concrete Surface Sealants," *Materials Information Report* No. M1-79, Ontario Ministry of Transportation and Communications, Downsview, 1985.

Bush, T., “Laboratory Test Procedures for Evaluating Concrete Treated with Sealers,” *ACI Materials Journal*, Vol. 95, No. 4, July-August, 1998, pp. 436-444.

Carter, P.D., and Forbes, A.J., “Comparative Evaluation of the Waterproofing and Durability of Concrete Sealers,” Report No. ABTR/RD/RR-86/09, Alberta Department of Transportation and Utilities, Edmonton, 1986.

Djazmati, B. et al., “Shear Stiffness and Strength of Horizontal Construction Joints,” University of Wisconsin-Madison Research Project, “Behavior of Deep Foundations Cast in Multiple Pours,” April, 2000.

Environmental Protection Agency (EPA), *National Volatile Organic Compound Emission Standards for Architectural Coatings,* Website: http://www.epa.gov/ttn/oarpg/t1/reports/aimbid.pdf. Last accessed October 2005

Geissert, D.G. et al., “Splitting Prism Test Method to Evaluate Concrete-to-Concrete Bond Strength,” *ACI Materials Journal*, Vol. 96, No. 3, May-June, 1999, pp. 359-366.

Hanson, N.W., “Precast – Prestressed Concrete Bridges 2. Horizontal Shear Connections,” Development Department Bulletin D 35, Portland Cement Association, 1960, pp. 38-58.

Henry, G., “Penetrating Water-Repellent Sealers,” *Concrete International,* Vol. 26, Issue 5, May, 2004, pp.81-83.

Krauss, P.D., and Boyd, S.R., “Cracking Repair Trials: City Island Bridge at US 61 and 151 Over the Mississippi River,” WJE No. 971345, Iowa Department of Transportation, 1999.

Krauss, P.D., and Rogalla, E.A., “Transverse Cracking in Newly Constructed Bridge Decks,” NCHRP Report 380, Transportation Research Board, National Research Council, Washington, DC, 1996, 126 pp.

Mood, A.M. et al., “Introduction to the Theory of Statistics,” McGraw-Hill, 1974.

Oklahoma Department of Transportation (OK DOT), *Method of Core Test for Determining Depth of Penetration of Penetrating Water Repellent Treatment Solution into Portland Cement Concrete,* OHD L-40, Oklahoma City, Oklahoma, 2003.

Paulay T., Park P., and Phillips M.H., “Horizontal Construction Joints in Cast-In-Place Reinforced Concrete, Shear in Reinforced Concrete,” SP-42, American Concrete Institute, Detroit, 1974, pp. 599-616.

Pfiefer, D., and Scali, M., “Concrete Sealers for Protection of Bridge Structures,” *NCHRP* 244, TRB, National Research Council, Washington, D.C., December, 1981.

State of Wisconsin, Department of Transportation, *Bridge Manual,* 2005.

State of Wisconsin, Department of Transportation, *Standard Specifications for Highway and Structure Construction,* 1996.

Appendix A: District Bridge Engineer Survey

		DECK SEALERS: WisDOT APPROVED														
		Aqua-Trete BSM 20	Baracade WB 244 (or Baracade 16 Siloxane)	Euco-guard 100	Hydrozo Enviroseal 20	Hydrozo Enviroseal 40	Hydrozo Silane 40 VOC	Masterseal SL 40 VOC	Nitecote Dekguard P-40	Penseal 244 40%	Powerseal 40%	Sonneborn Penetrating Sealer 40 VOC	Spall-Guard 40	TK-290-WBG	TK-290-WDOT (or TK-290-16)	TK-290-WDOT E
	General															
1.	How long have you been specifying this product? (Leave blank if product not used.)															
	a.) 1 year or less															
	b.) 1-5 years															
	c.) more than 5 years															
2.	Please indicate the ease of application of this product:															
	a.) easy and quick to apply															
	b.) moderately difficult and time consuming to apply															
	c.) very difficult and time consuming to apply															
	Durability & Performance of Product															
3.	On average, how often does the product need to be applied to the same surface?															
	a.) every 1 year															
	b.) every 2 years															
	c.) every 5 years															
	d.) every 10 years															
	e.) other, please specify ___________________________															
4.	For **NEW DECKS** subjected to similar traffic and environmental conditions, the product:															
	a.) delayed deterioration since application of the product															
	b.) resulted in no visible change since application of the product															
	c.) increased the rate of deterioration since application of the product															
5.	For **EXISTING DECKS** subjected to similar traffic and environmental conditions, the product:															
	a.) delayed deterioration since application of the product															
	b.) resulted in no visible change since application of the product															
	c.) increased the rate of deterioration since application of the product															

Would you be available for a follow-up interview if more information is needed? **NO** ______________ **YES** ______________ **Phone #** __________________________

	DECK AND CRACK SEALERS: NOT WisDOT APPROVED																			**OTHERS**		
	TK-2671	TK-290 Tri-Siloxane	TK-290 WB Tri-Siloxane	Degadeck Crack Sealer	Denepox I-40	Denepox I-60	Duralcrete LV	Eucopoxy Injection Resin	Sikadur 52	Sikadur 55SLV	TK-9000	TK-9010 Crack & Joint Repair	TK-9020 Crack & Joint Repair	TK-9030 Crack & Joint Repair	10 Minute Concrete Mender	Duraguard 100	Duraguard 401	Dural 335	TK-26			
General																						
1. How long have you been specifying this product? (Leave blank if product not used.)																						
a.) 1 year or less																						
b.) 1-5 years																						
c.) more than 5 years																						
2. Please indicate the ease of application of this product:																						
a.) easy and quick to apply																						
b.) moderately difficult and time consuming to apply																						
c.) very difficult and time consuming to apply																						
Durability & Performance of Product																						
3. On average, how often does the product need to be applied to the same surface?																						
a.) every 1 year																						
b.) every 2 years																						
c.) every 5 years																						
d.) every 10 years																						
e.) other, please specify __________________________																						
4. For **NEW DECKS** subjected to similar traffic and environmental conditions, the product:																						
a.) delayed deterioration since application of the product																						
b.) resulted in no visible change since application of the product																						
c.) increased the rate of deterioration since application of the product																						
5. For **EXISTING DECKS** subjected to similar traffic and environmental conditions, the product:																						
a.) delayed deterioration since application of the product																						
b.) resulted in no visible change since application of the product																						
c.) increased the rate of deterioration since application of the product																						
Would you be available for a follow-up interview if more information is needed?	**NO** _____________ **YES** _____________ **Phone #** ________________________																					

Appendix B: Summary of Chloride Ion Analysis Results

Concrete Batch #1 - Exposed to Freeze-Cycles

Treatment Condition	Average/hole (lb Cl^-/yd^3)	Average/specimen (lb Cl^-/yd^3)	Overall Average (lb Cl^-/yd^3)	Average absorbed chloride (lb Cl^-/yd^3)
Unsealed (Control)	1.46	1.52	1.52 (0.19) *	N/A
	1.34			
	1.74			
Unsealed	6.50	7.32	7.43 (1.40)	5.92
	5.61			
	9.86			
	7.99	7.65		
	6.32			
	8.64			
	8.62	7.33		
	7.38			
	5.98			
TK 290-WB	7.73	7.81	7.77 (1.49)	6.26
	6.56			
	9.13			
	4.99	6.37		
	7.82			
	6.31			
	9.11	9.14		
	9.25			
	9.06			
Baracade WB 244	8.41	7.35	8.03 (1.27)	6.52
	7.57			
	6.08			
	8.20	7.28		
	6.61			
	7.01			
	9.44	9.47		
	9.75			
	9.23			

* Values in parentheses show the standard deviation of the results

Concrete Batch #2 - Exposed to Freeze-Cycles

Treatment Condition	Average/hole (lb Cl^-/yd^3)	Average/specimen (lb Cl^-/yd^3)	Overall Average (lb Cl^-/yd^3)	Average absorbed chloride (lb Cl^-/yd^3)
Unsealed (Control)	1.83	1.54	1.54 (0.24)*	N/A
	1.45			
	1.34			
Unsealed	11.02	9.73	7.85 (2.17)	6.31
	9.83			
	8.34			
	5.08	5.35		
	6.40			
	4.56			
	9.69	8.46		
	8.78			
	6.92			
Hydrozo Enviroseal 20	6.96	6.43	6.12 (1.15)	4.58
	5.52			
	6.80			
	4.05	4.83		
	5.08			
	5.36			
	7.51	7.12		
	7.45			
	6.38			
Hydrozo Enviroseal 40	6.24	5.83	6.30 (1.38)	4.76
	4.87			
	6.39			
	4.45	5.49		
	6.32			
	5.70			
	6.21	7.57		
	7.10			
	9.39			

* Values in parentheses show the standard deviation of the results

Concrete Batch #3 - Exposed to Freeze-Cycles

Treatment Condition	Average/hole (lb Cl-/yd3)	Average/specimen (lb Cl-/yd3)	Overall Average (lb Cl-/yd3)		Average absorbed chloride (lb Cl-/yd3)
Unsealed (Control)	1.67	1.37	1.37	(0.24)*	N/A
	1.26				
	1.18				
Unsealed	8.39	8.52	8.45	(1.21)	7.08
	9.03				
	8.15				
	8.71	7.47			
	8.22				
	5.47				
	9.60	9.37			
	8.86				
	9.63				
Aqua-Trete BSM 20	6.85	7.74	8.36	(1.39)	6.99
	8.75				
	7.62				
	10.08	8.25			
	6.87				
	7.82				
	10.56	9.10			
	9.63				
	7.10				
TK 290 WDOT	5.54	5.80	7.02	(1.09)	5.65
	6.00				
	5.86				
	7.49	7.63			
	8.28				
	7.13				
	6.54	7.64			
	8.79				
	7.58				

* Values in parentheses show the standard deviation of the results

Concrete Batch #4 - Exposed to Freeze-Cycles

Treatment Condition	Average/hole (lb Cl$^-$/yd^3)	Average/specimen (lb Cl$^-$/yd^3)	Overall Average (lb Cl$^-$/yd^3)	Average absorbed chloride (lb Cl$^-$/yd^3)
Unsealed (Control)	1.83	1.60	1.60 (0.25)*	N/A
	1.66			
	1.30			
Unsealed	5.45	6.07	6.04 (0.31)	4.44
	6.32			
	6.43			
	5.94	5.98		
	5.98			
	6.03			
	6.21	6.07		
	5.93			
	6.08			
Sonneborn Penetrating Sealer 40 VOC	3.23	3.56	3.11 (0.75)	1.51
	2.75			
	4.68			
	2.66	2.74		
	2.36			
	3.21			
	2.70	3.03		
	2.46			
	3.94			
Hydrozo Silane 40 VOC	3.84	4.15	4.30 (1.06)	2.71
	5.29			
	3.31			
	4.70	4.66		
	2.98			
	6.29			
	4.96	4.11		
	4.10			
	3.28			

* Values in parentheses show the standard deviation of the results

Concrete Batch #5 - Not Exposed to Freeze-Cycles

Treatment Condition	Average/hole (lb Cl^-/yd^3)	Average/specimen (lb Cl^-/yd^3)	Overall Average (lb Cl^-/yd^3)	Average absorbed chloride (lb Cl^-/yd^3)
Unsealed (Control)	1.45	1.46	1.46 (0.13)*	N/A
	1.41			
	1.32			
	1.66			
Unsealed	8.11	7.24	6.55 (0.73)	5.09
	6.94			
	6.66			
	6.54	6.02		
	6.17			
	5.33			
	6.15	6.39		
	6.29			
	6.74			
TK-290 WB	5.39	5.61	7.10 (1.38)	5.64
	4.88			
	6.57			
	6.84	7.27		
	8.49			
	6.49			
	8.35	8.41		
	8.90			
	7.97			
Baracade WB 244	7.38	7.94	7.11 (1.11)	5.66
	8.57			
	7.85			
	7.53	7.42		
	6.64			
	8.11			
	6.54	5.98		
	4.73			
	6.66			

* Values in parentheses show the standard deviation of the results

Concrete Batch #6 - Not Exposed to Freeze-Cycles

Treatment Condition	Average/hole (lb Cl^-/yd^3)	Average/specimen (lb Cl^-/yd^3)	Overall Average (lb Cl^-/yd^3)	Average absorbed chloride (lb Cl^-/yd^3)
Unsealed (Control)	1.22	1.21	1.21 (0.08)*	N/A
	1.30			
	1.12			
Unsealed	5.53	6.14	6.98 (1.27)	5.77
	7.20			
	5.68			
	6.09	7.05		
	5.98			
	9.08			
	8.90	7.76		
	7.45			
	6.93			
Aqua-Trete BSM 20	6.62	5.56	6.07 (1.32)	4.86
	3.09			
	6.96			
	6.30	6.62		
	6.61			
	6.95			
	5.13	6.03		
	5.45			
	7.52			
TK 290 Tri-Siloxane	6.05	6.17	6.15 (0.75)	4.93
	6.81			
	5.66			
	6.47	5.75		
	4.57			
	6.20			
	7.27	6.52		
	6.42			
	5.87			

* Values in parentheses show the standard deviation of the results

Concrete Batch #7 - Not Exposed to Freeze-Cycles

Treatment Condition	Average/hole (lb Cl^-/yd^3)	Average/specimen (lb Cl^-/yd^3)	Overall Average (lb Cl^-/yd^3)	Average absorbed chloride (lb Cl^-/yd^3)
Unsealed (Control)	1.44	1.44	1.44 (0.13)*	N/A
	1.58			
	1.30			
Unsealed	5.70	5.58	6.05 (1.26)	4.61
	6.02			
	5.01			
	5.19	5.05		
	4.14			
	5.82			
	7.29	7.51		
	8.27			
	6.98			
Hydrozo Enviroseal 20	7.94	6.42	6.27 (1.26)	4.83
	5.62			
	5.68			
	6.82	5.66		
	4.21			
	5.94			
	6.36	6.72		
	5.43			
	8.39			
Hydrozo Enviroseal 40	2.74	4.94	5.49 (2.17)	4.06
	5.01			
	7.06			
	3.44	3.69		
	4.05			
	3.58			
	6.88	7.85		
	9.21			
	7.47			

* Values in parentheses show the standard deviation of the results

Concrete Batch #8 - Not Exposed to Freeze-Cycles

Treatment Condition	Average/hole (lb Cl$^-$/yd^3)	Average/specimen (lb Cl$^-$/yd^3)	Overall Average (lb Cl$^-$/yd^3)	Average absorbed chloride (lb Cl$^-$/yd^3)
Unsealed (Control)	1.47	1.28	1.28 (0.22)*	N/A
	1.01			
	1.36			
Unsealed	5.50	5.74	5.52 (0.71)	4.24
	5.40			
	6.31			
	5.12	5.90		
	5.54			
	7.03			
	4.71	4.92		
	4.96			
	5.08			
Sonneborn Penetrating Sealer 40 VOC	3.84	4.51	3.23 (1.17)	1.96
	4.71			
	4.97			
	2.36	2.63		
	1.60			
	3.94			
	2.09	2.56		
	3.21			
	2.37			
Hydrozo Silane 40 VOC	2.88	2.93	2.87 (1.00)	1.59
	2.30			
	3.61			
	1.85	1.87		
	1.57			
	2.20			
	4.43	3.80		
	2.71			
	4.26			

* Values in parentheses show the standard deviation of the results

Concrete Batch #9 - Not Exposed to Freeze-Cycles

Treatment Condition	Average/hole (lb Cl$^-$/yd^3)	Average/specimen (lb Cl$^-$/yd^3)	Overall Average (lb Cl$^-$/yd^3)	Average absorbed chloride (lb Cl$^-$/yd^3)
Unsealed (Control)	1.52	1.45	1.45 (0.10)*	N/A
	1.39			
	1.45			
Unsealed	3.37	3.06	4.26 (1.01)	2.81
	3.31			
	2.50			
	4.96	5.13		
	5.83			
	4.61			
	5.15	4.59		
	4.40			
	4.21			
Eucoguard 100	3.84	3.70	5.01 (1.77)	3.55
	3.68			
	3.58			
	8.34	7.22		
	6.80			
	6.53			
	4.52	4.10		
	2.88			
	4.89			
Aquanil Plus 40	3.38	3.14	2.86 (0.71)	1.41
	3.82			
	2.23			
	4.10	3.14		
	2.74			
	2.58			
	2.04	2.30		
	2.53			
	2.32			

* Values in parentheses show the standard deviation of the results

Concrete Batch #10 - Not Exposed to Freeze-Cycles

Treatment Condition	Average/hole (lb Cl$^-$/yd^3)	Average/specimen (lb Cl$^-$/yd^3)	Overall Average (lb Cl$^-$/yd^3)	Average absorbed chloride (lb Cl$^-$/yd^3)
Unsealed (Control)	1.73	1.69	1.69 (0.27)*	N/A
	1.99			
	1.36			
Unsealed	5.93	5.55	5.62 (0.76)	3.93
	6.03			
	4.68			
	5.45	5.40		
	5.76			
	4.98			
	7.34	5.93		
	5.37			
	5.09			
V-Seal	5.05	4.58	4.73 (0.96)	3.04
	4.98			
	3.71			
	4.70	4.30		
	5.46			
	2.74			
	4.52	5.31		
	5.45			
	5.96			
Penseal 244	1.60	2.84	3.91 (2.18)	2.22
	1.90			
	2.64			
	5.20			
	3.42	5.84		
	8.06			
	5.66			
	3.93			
	8.11			
	3.47	3.07		
	1.82			
	4.90			
	2.10			

* Values in parentheses show the standard deviation of the results

Concrete Batch #11 - Not Exposed to Freeze-Cycles

Treatment Condition	Average/hole (lb Cl^-/yd^3)	Average/specimen (lb Cl^-/yd^3)	Overall Average (lb Cl^-/yd^3)	Average absorbed chloride (lb Cl^-/yd^3)
Unsealed (Control)	1.23	1.47	1.47 (0.20)*	N/A
	1.61			
	1.59			
Unsealed	5.38	6.07	5.73 (1.00)	4.26
	5.60			
	7.24			
	4.42	4.62		
	4.62			
	4.81			
	6.18	6.50		
	6.24			
	7.08			
Powerseal 40%	5.61	5.39	4.73 (0.88)	3.26
	4.91			
	5.66			
	2.95	4.50		
	4.87			
	5.68			
	4.07	4.30		
	4.73			
	4.11			

* Values in parentheses show the standard deviation of the results

Concrete Batch #12 - Exposed to Freeze-Cycles

Treatment Condition	Average/hole (lb Cl$^-$/yd^3)	Average/specimen (lb Cl$^-$/yd^3)	Overall Average (lb Cl$^-$/yd^3)	Average absorbed chloride (lb Cl$^-$/yd^3)
Unsealed (Control)	1.37	1.27	1.27 (0.20)*	N/A
	1.44			
	1.02			
Unsealed	4.99	5.06	5.43 (0.71)	4.15
	4.61			
	5.56			
	5.48	5.99		
	5.67			
	6.81			
	5.93	5.23		
	5.40			
	4.38			
Eucoguard 100	4.47	5.13	5.82 (1.35)	4.54
	4.31			
	6.60			
	4.87	6.27		
	6.05			
	7.90			
	5.83	6.05		
	7.79			
	4.53			
Aquanil Plus 40	5.70	5.06	5.98 (1.73)	4.70
	4.55			
	4.94			
	8.77	8.00		
	7.08			
	8.15			
	6.61	4.87		
	3.93			
	4.05			

* Values in parentheses show the standard deviation of the results

Concrete Batch #13 - Exposed to Freeze-Cycles

Treatment Condition	Average/hole (lb Cl⁻/yd³)	Average/specimen (lb Cl⁻/yd³)	Overall Average (lb Cl⁻/yd³)	Average absorbed chloride (lb Cl⁻/yd³)
Unsealed (Control)	1.30	1.39	1.39 (0.09)*	N/A
	1.48			
	1.38			
Unsealed	4.17	4.92	5.03 (1.29)	3.65
	4.31			
	6.29			
	3.99	3.96		
	4.03			
	3.85			
	7.63	6.22		
	4.98			
	6.05			
V-Seal	7.80	6.95	4.95 (1.63)	3.56
	7.16			
	5.89			
	3.76	3.63		
	4.00			
	3.12			
	4.27	4.26		
	3.35			
	5.17			
Penseal 244	4.47	5.13	5.23 (2.14)	3.84
	4.63			
	6.29			
	6.09	7.57		
	7.68			
	8.93			
	3.42	2.99		
	2.04			
	3.50			

* Values in parentheses show the standard deviation of the results

Concrete Batch #14 - Exposed to Freeze-Cycles

Treatment Condition	Average/hole (lb Cl^-/yd^3)	Average/specimen (lb Cl^-/yd^3)	Overall Average (lb Cl^-/yd^3)	Average absorbed chloride (lb Cl^-/yd^3)
Unsealed (Control)	1.76	1.72	1.72 (0.11)*	N/A
	1.81			
	1.59			
Unsealed	4.46	4.75	4.97 (0.96)	3.25
	5.50			
	4.31			
	5.56	4.52		
	3.96			
	4.05			
	5.82	5.63		
	6.80			
	4.28			
Powerseal 40%	3.94	4.43	4.49 (0.43)	2.77
	4.73			
	4.63			
	4.38	4.43		
	4.06			
	4.87			
	4.84	4.61		
	3.90			
	5.10			

* Values in parentheses show the standard deviation of the results

Appendix C

Calculation of Adjusted Absorbed Chloride Content

Since the specimens subjected to freeze-thaw cycles were fabricated from a different batch than that used for the specimens not subjected to freeze-thaw cycles, the difference in chloride content of the mix itself needed to be considered in the comparison presented in section 6.2.2.2b.

When all specimens are fabricated from the same batch, the absorbed chloride of an unsealed specimen not exposed to freeze-thaw cycles is calculated as the difference between the total chloride of the unsealed ponded specimen, Cl_{NoF-T}^{U-P}, and that of the control specimen (unsealed and not ponded), $Cl^{Control}$. Thus,

$$\Delta Cl_{No\,F-T}^{U-P} = Cl_{NoF-T}^{U-P} - Cl^{Control} \tag{C-1}$$

where:

$\Delta Cl_{No\,F-T}^{U-P}$ = absorbed chloride ion content for an unsealed ponded specimen

Cl_{NoF-T}^{U-P} = total chloride ion content of an unsealed ponded specimen not subjected to freeze-thaw cycles

$Cl^{Control}$ = baseline chloride ion content from the unsealed, not ponded, control specimen from the corresponding batch

To account for variations in the chloride content from different batches, the absorbed chloride content has to be adjusted by the difference between the chloride contents of the control specimens in each batch. Thus, equation (C-1) may be rewritten as:

$$\Delta Cl_{Adjusted}^{U-P} = Cl_{NoF-T}^{U-P} - Cl^{Control} + \Delta Cl^{Control} \tag{C-2}$$

where:

$\Delta Cl_{Adjusted}^{U-P}$ = absorbed chloride ion content for an unsealed ponded specimen adjusted for the difference in chloride content from different batches

$\Delta Cl^{Control}$ = difference in chloride content from different batches and Cl_{NoF-T}^{U-P} , $Cl^{Control}$, have been defined above.

Since the basis for the comparison in section 6.2.2.2b is the specimen subjected to freeze-thaw cycles, equation (C-2) becomes:

$$\Delta Cl_{Adjusted}^{U-P} = Cl_{NoF-T}^{U-P} - Cl_{F-T}^{Control} + (Cl_{No\,F-T}^{Control} - Cl_{F-T}^{Control}) \qquad \text{(C-3)}$$

where

$Cl_{F-T}^{Control}$ = baseline chloride ion content from the unsealed, not ponded, control specimen from the batch of sealed specimens *subjected* to freeze-thaw cycles

$Cl_{No\,F-T}^{Control}$ = baseline chloride ion content from the unsealed, not ponded, control specimen from the batch of sealed specimens *not subjected* to freeze-thaw cycles

Equation (C-3) was used to compute the absorbed chloride content of the unsealed specimens shown in Table 6.2.5.

Appendix D

Calculation of Adjusted Total Chloride Content

Since the specimens subjected to freeze-thaw cycles were fabricated from a different batch than that used for the specimens not subjected to freeze-thaw cycles, the difference in chloride content of the mix itself needed to be considered in the comparison presented in section 6.3.3.2. To account for this difference, an adjusted total chloride ion content (shown in Table 6.3.5) for the unsealed specimens was computed as follows:

$$Cl_{Adjusted}^{U-P} = Cl_{No\ F-T}^{U-P} + Cl_{F-T}^{Control} - Cl_{No\ F-T}^{Control} \qquad \text{(D-1)}$$

where: $Cl_{Adjusted}^{U-P}$ = adjusted total chloride ion content for unsealed ponded specimens

Cl_{NoF-T}^{U-P} = total chloride ion content of unsealed ponded specimens *not* subjected to freeze-thaw cycles

$Cl_{NoF-T}^{Control}$ = baseline chloride ion content from unsealed, not ponded, control specimens from the batch *not subjected* to freeze-thaw cycles

$Cl_{F-T}^{Control}$ = baseline chloride ion content from unsealed, not ponded, control specimens from the batch *subjected* to freeze-thaw cycles